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HELICOPTER DRIVE SYSTEM ON-CONDITION MAINTENANCE CAPABILITY

Sikorsky Aircraft Division
United Technologies Corporation
Stratford, Conn. 06602

July 1976

Final Report

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U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
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EUSTIS DIRECTORATE POSITION STATEMENT

This report presents an assessment of the capability of CH-53 and CH-54 helicopter drive system components to operate without the necessity for mandatory scheduled overhaul periods. Achievement of an on-condition maintenance policy is recognized as offering significant life-cycle cost savings over the establishment of "Time-Between-Overhauls" (TBO) periods. The conclusions and recommendations contained herein are concurred in by this Directorate.

This report is one of a series dealing with the subject of helicopter drive system component scheduled overhaul periods. "Analysis of Criteria for On-Condition Maintenance for Helicopter Transmissions" (USAAMRDL Technical Report 73-58) provides a methodology for performing an on-condition assessment and applies that methodology to the CH-47. "Helicopter Drive System On-Condition Maintenance Capability (UH-1/AH-1)" applies a similar methodology to the UH-1/AH-1. These efforts indicate that the UH-1, AH-1, CH-47, CH-53, and CH-54 aircraft transmissions and gearboxes are capable of operating without mandatory scheduled overhaul periods. This Directorate plans to develop a drive system reliability and maintainability design guide that will incorporate the findings of this effort. The design guide will address, among other issues, the design concepts and procedures that most significantly enhance on-condition operation.

Victor W. Weiner of the Military Operations Technology Division served as project engineer for this effort.

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This report presents the results of a study that was conducted to determine the feasibility of operating CH-53/54 gearboxes without any scheduled removals for overhaul, that is, being maintained on-condition. A reliability analysis technique was developed to establish gearbox hazard functions, which express the relationship between the equipment failure rate and its operating time. Furthermore, design concepts and procedures were identified which enhance on-condition maintenance for CH-53/54 gearboxes.

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All CH-53/54 gearboxes are capable of being maintained without any specified overhaul period (on-condition) on the basis of their projected hazard functions at 5000 operating hours. Certain design changes and procedures are recommended before an on-condition maintenance policy is initiated. While many of these are not essential, they are desirable to improve product reliability. These improvements are practical and feasible with virtually no increase in the weight of any CH-53/54 gearbox. Current inspection techniques and diagnostic devices are adequate for implementing an on-condition maintenance policy. Concurrent with the initiation of an on-condition maintenance policy, it is recommended that field and depot maintenance of on-condition gearboxes be monitored. The fact that data for this study was obtained from aircraft that flew in Vietnam where they saw overtorque situations reinforces the practicality of an on-condition maintenance philosophy for the transmission system.

The reliability analysis technique developed by this study used hazard functions of individual generic component failure modes as building blocks to construct the gearbox level hazard function for each category of failure mode. The method permits evaluation of current design practices. Its real benefit is that it will allow future gearbox reliability requirements to be evaluated by the designer so that reliability is understood and designed in.

PREFACE

This study was conducted for the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory (USAAMRDL), Fort Eustis, Virginia, under Contract DAAJ02-74-C-0045.

USAAMRDL technical direction was provided by Mr. V. Welner and Mr. T. House.

The Sikorsky Aircraft personnel involved in performing or assisting in this study were:

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- Mr. A. Angelovich, Reliability Engineer
- Mr. G. Geffert, Reliability Engineer

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1. INTRODUCTION

1.1 BACKGROUND

Contract No. DAAJ02-72-C-0068's analysis of criteria for on-condition maintenance for helicopter transmissions resulted in a methodology for assessing the capability of helicopter dynamic components to operate without the need for scheduled removals and an application of that methodology to the CH-47. The conclusions reached under that effort reflect the operational experience of the CH-47. Analysis of the CH-53/54 transmission systems was undertaken to gain the experience of other helicopter systems and to formulate a clear position concerning on-condition maintenance for helicopter drive systems and to identify those design concepts and procedures which would significantly enhance this approach.

The work done under Contract No. DAAJ02-72-C-0068 and documented in USAARMDL TR 73-58[1] resulted in an evaluation of on-condition maintenance criteria from estimated hazard functions that describe the relationship between a gearbox's operating time and its failure rate. Research of other existing reliability analysis techniques was undertaken to develop a preferred analysis concept for establishing gearbox hazard functions.

The notion of hazard functions is not new to reliability analysis. The classical "bathtub" curve is familiar to everyone for describing an equipment's failure rate as a function of operating time. The term hazard function is synonymous with instantaneous failure rate. Hazard functions developed in this study for each failure mode describe only one section of the "bathtub" curve. Thus, it would be necessary to combine three hazard functions to completely describe the "bathtub" curve: one describing infant mortality failures, one describing random failures, and one describing wearout failures. While this study concentrates on determining which section of the "bathtub" curve best described the failure mode's behavior, the approach developed is sensitive enough to know when two or more different hazard functions are needed. The shaft seals of the CH-53 tail rotor gearbox, for example, were found to exhibit an infant mortality type hazard function as well as a wearout type hazard function.

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[1] Dougherty, J. J., and Blewitt, S. J., "Analysis of Criteria for On-Condition Maintenance for Helicopter Transmissions", USAARMDL Technical Report 73-58, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, September 1973.

1.2 APPROACH

The reliability analysis technique for establishing gearbox hazard functions is based upon the reliability distribution defined by the Weibull reliability function. The Weibull distribution defines the cumulative reliability, R(t), as follows:

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$

where β is called the shape parameter and θ the size parameter. The hazard function, $h(t)$, which is defined as the instantaneous failure rate at any time, is given as follows:

$$h(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}$$

The relationship between reliability and the hazard function is

$$R(t) = e^{-\int_0^t h(\S)d\S}$$

where § is used as an integration variable to permit evaluation of the integral.

The reliability analysis technique establishes gearbox hazard functions for safety-of-flight failure modes, mission reliability failure modes, and dynamic component removal failure modes. The analysis starts by defining and categorizing generic device failure modes in terms of their worst possible effect on aircraft performance from the criteria given in Table 1. The impact of current gearbox inspection techniques and diagnostic systems is then evaluated to determine their ability to alleviate the risk associated with the occurrence of a failure mode or to classify a failure mode, for example, from safety of flight to mission reliability. Once the worst-case categorization has been established, the others easily follow. Hazard functions are then established for each generic device failure mode either from experience data or from various estimation methods when no experience data are available. Finally, all the hazard functions of a particular category (safety of flight, mission reliability, dynamic component removal) are combined and the resultant hazard function is plotted.

The details and the derivation of the complete technical approach employed in this study are given in Appendix A.

TABLE 1. FAILURE MODE CATEGORIZATION CRITERIA

Category	
Safety-of-Flight Failure Mode	A failure mode that causes either immediate forced landing, injury to the crew, or catastrophic loss of the vehicle.
Mission Reliability Failure Mode	A failure mode which prevents commencement or completion of a mission, either by rendering the system incapable of performing the primary function of the mission or by exposing the vehicle occupants to unacceptable flight risk if the mission is begun or continued.
Dynamic Component Failure Mode	A failure mode that causes the removal of a component and replacement with a like item.

1.3 CH-53/54 TRANSMISSION SYSTEM DESCRIPTION

This study examines the CH-54 and the CH-53 Transmission systems. The CH-53 transmission system is comprised of five gearboxes: (1) nose gearbox, (2) main gearbox, (3) intermediate gearbox, (4) tail rotor gearbox, and (5) accessory gearbox. The CH-54 has three gearboxes: (1) main gearbox, (2) intermediate gearbox, and (3) tail rotor gearbox.

1.3.1 CH-54 MAIN GEARBOX

The CH-54 main gearbox changes the angle of drive from the engines to the main rotor and reduces rpm. (see Figures 1 and 2.) It supports and drives the main rotor and accessories, and provides power through the tail rotor drive shaft driving the tail rotor. Accessories are driven from the tail takeoff gear. A rotor brake stops rotor head rotation after both engines are shut down. The rotor brake is spline coupled into the second-stage pinion gear shaft. Lubrication is accomplished by self-priming wet sump system. The oil pump, attached to the main gearbox sump, circulates oil for the main gearbox lubrication and cooling. The gearbox is equipped with an oil filter and oil strainer. A magnetic chip detector in the sump is part of the chip detector system. A transmitter sends oil pressure readings to an indicator on the instrument panel, while a temperature bulb in the oil strainer transmits oil temperature readings to an indicator on the instrument panel. Freewheel units isolate engine torque from the main gearbox when a reduction in an engine's input speed causes the second-stage pinion gear to rotate faster than the first-stage bevel gear. The auxiliary power plant may be used for operating the main gearbox accessories without turning the rotors by a freewheel unit located on the tail rotor takeoff pinion gear shaft.

Not all aircraft accessories are driven by the main gearbox. The second-stage hydraulic pump is directly driven from an engine. This prevents any single gearbox malfunction from causing the complete loss of accessory power.

1.3.2 CH-54 INTERMEDIATE GEARBOX

The CH-54 intermediate gearbox transmits torque from the tail drive shaft to the pylon drive shaft, changing the angle and direction of drive (see Figure 3). The gearbox consists of an input housing, center housing, and output housing. The input and output housings contain input and output spiral bevel gears and flanges. The center housing contains the idler gear, oil pump, sight gage, and chip detector. The gearbox is air cooled while the oil pump circulates the oil for lubrication.

1.3.3 CH-54 TAIL ROTOR GEARBOX

The CH-54 tail rotor gearbox serves as the point of attachment for the tail rotor, transmits torque from the pylon drive shaft to the tail rotor, and changes angle of drive 90 degrees. The gearbox consists of a horn assembly, and of input, center, and output housings (see Figure 4). The gearbox is splash lubricated and air cooled. The input housing contains the chip detector plug, and the output housing contains the filler plug and oil level sight gage. The tail rotor tandem servocylinder, installed through the gearbox, is controlled by the directional flight controls and operates the pitch beam which in turn is connected by links to the sleeve of each tail rotor blade and changes blade pitch.

1.3.4 CH-53 NOSE GEARBOX

The CH-53 has two nose gearboxes mounted on the exterior of the main fuselage over and outboard of the forward cabin section. Each gearbox is mounted at the forward section of an engine and serves as a forward engine mount. The nose gearbox transmits engine torque to the main gearbox through the main gearbox input drive shaft (see Figures 5 through 7). Each gearbox provides the initial rpm reduction and changes the angle of drive from the engine to the main gearbox. Each gearbox consists of a front cover assembly, center housing linear and stud assembly, input housing and gear assembly, output housing and gear assembly, oil pump, oil dipstick, strainer and filter, electric chip detector, oil pressure switch for the oil pressure indicating system, and a plugstat for the oil temperature indicating system. Each gearbox provides a drive pad for the fuel control flex drive, tachometer-generator, and speed-sensing switch, and a driver pulley to drive the engine and nose gearbox oil cooler assembly. Lubrication of the gearbox is accomplished by a wet sump system. A gear type

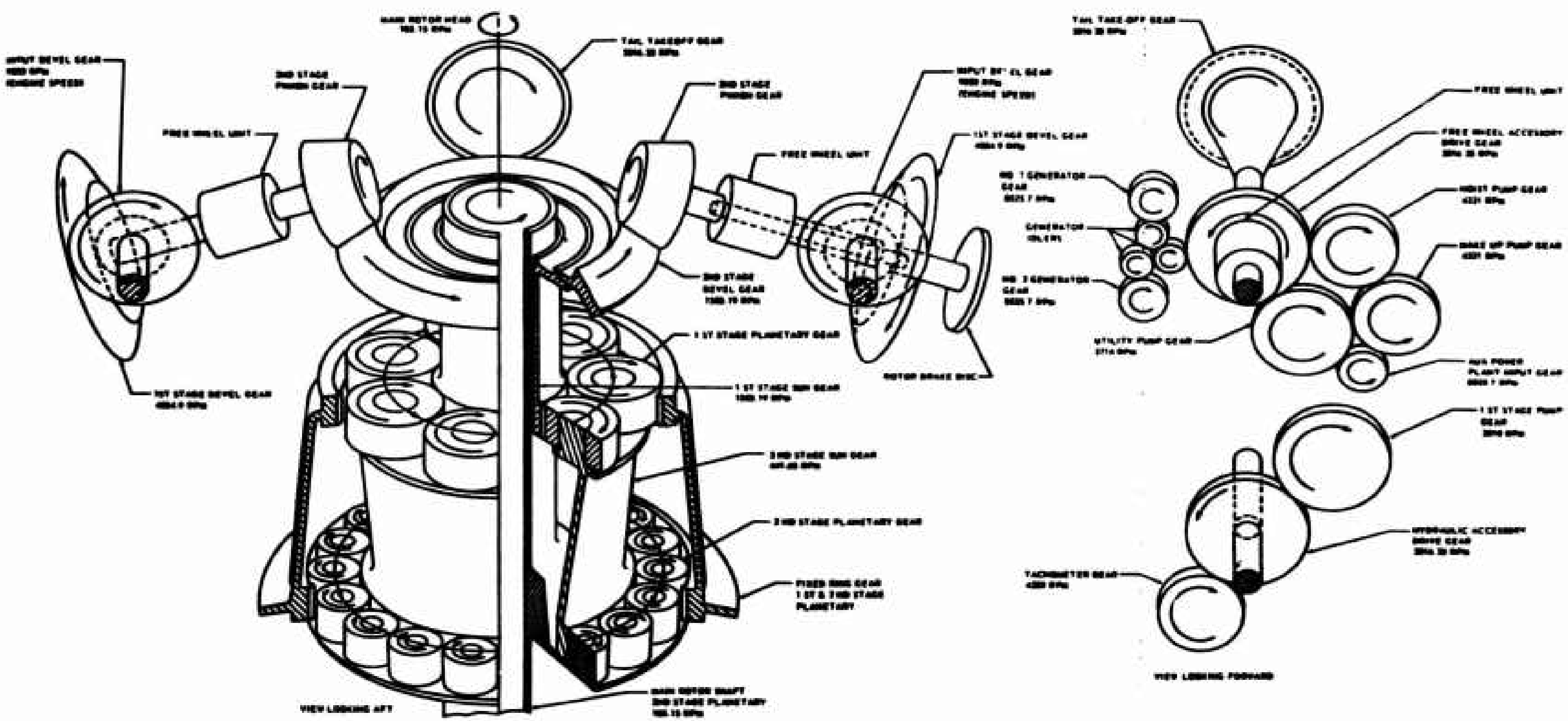


Figure 1. CH-54 Main Drive Train Schematic.

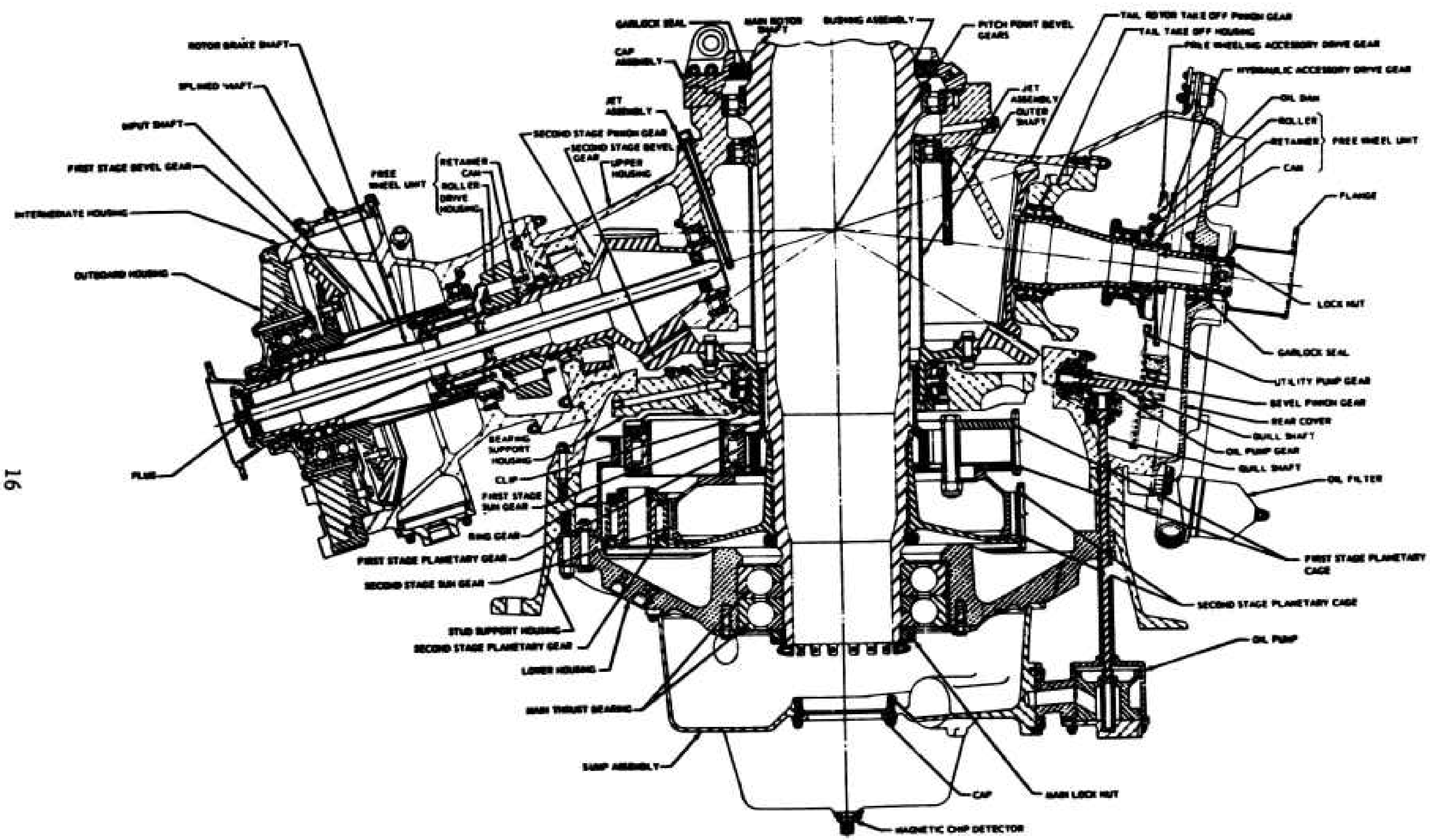
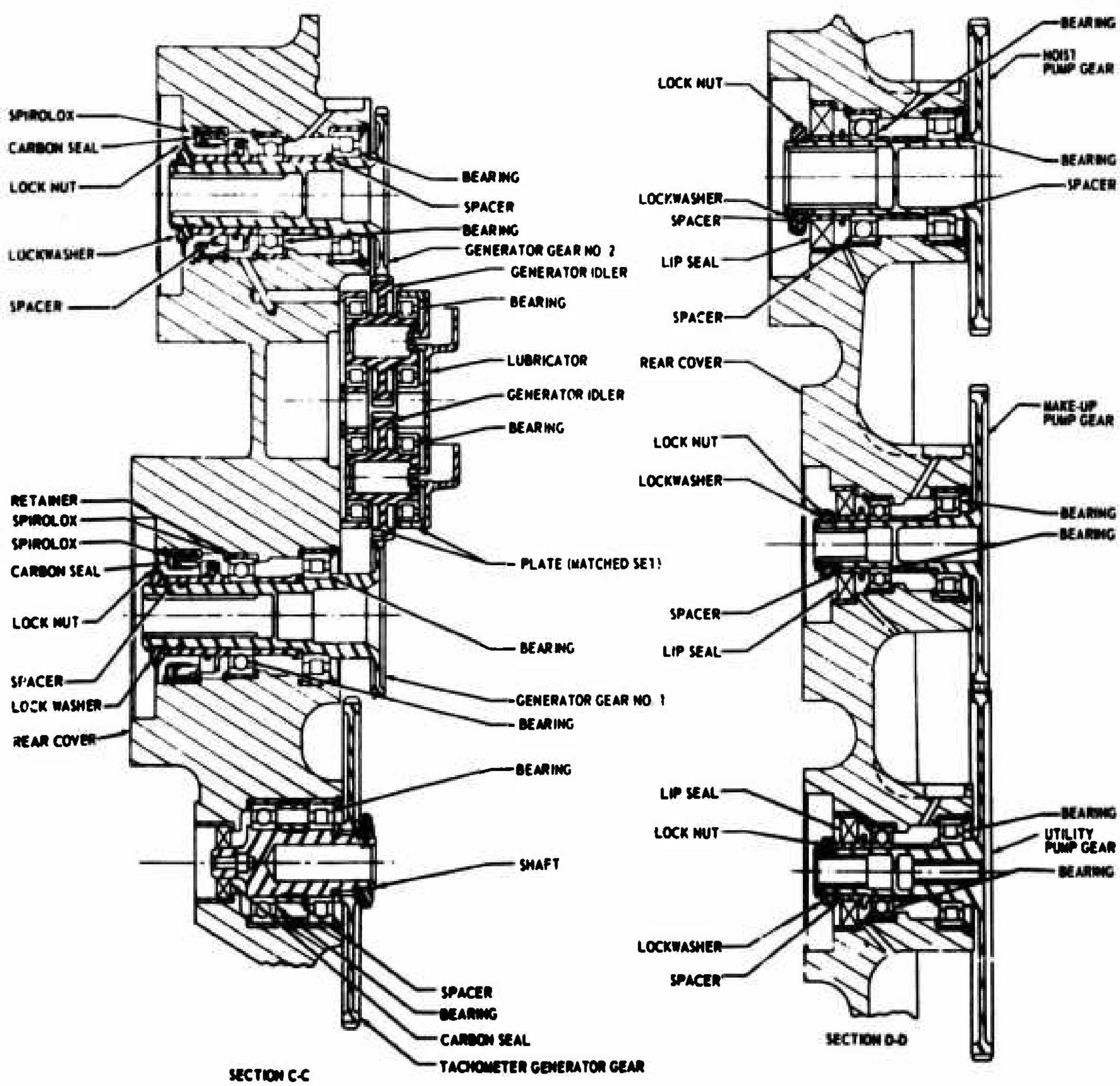


Figure 2. CH-54 Main Gearbox Cross-Sectional View.



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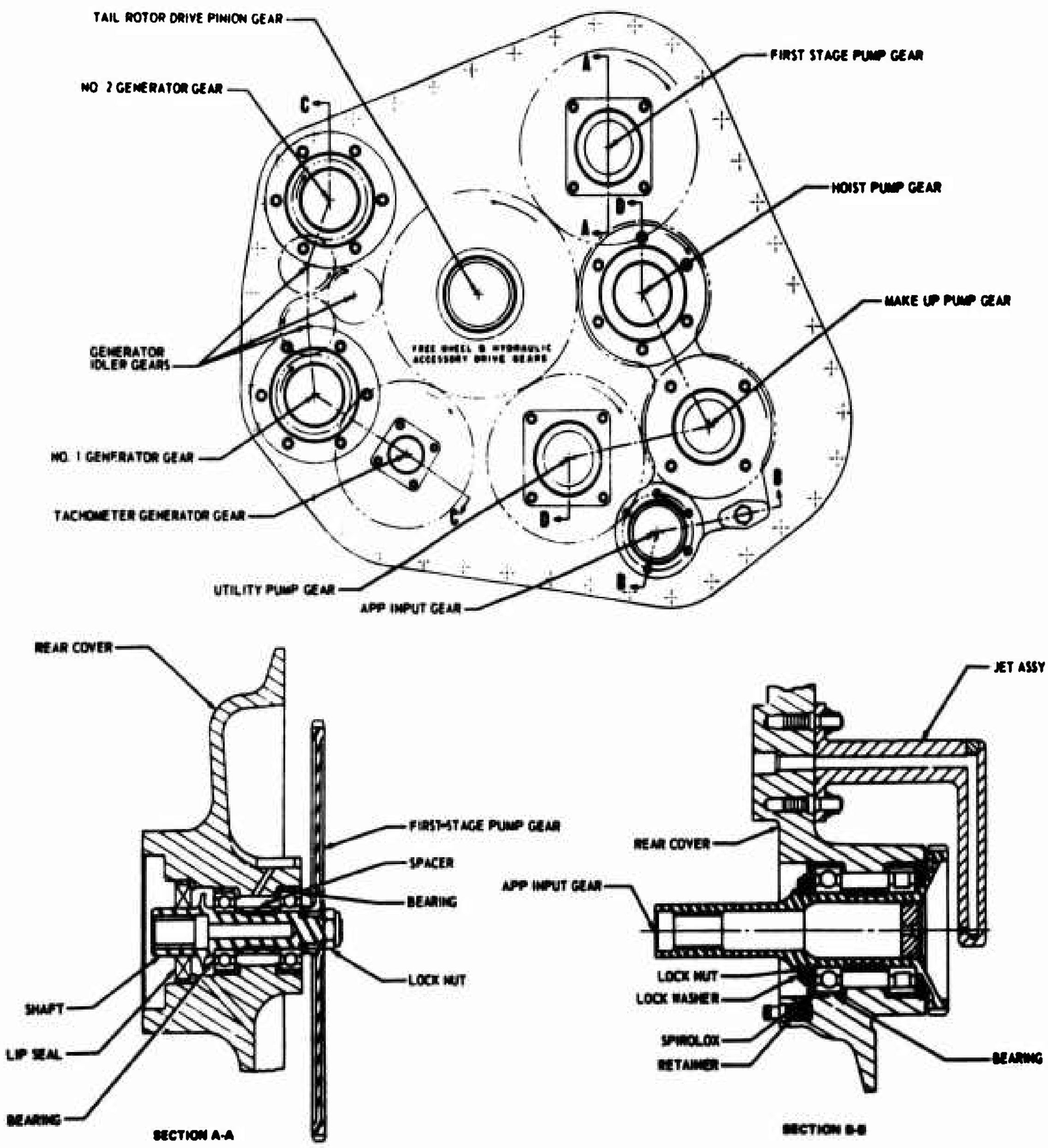

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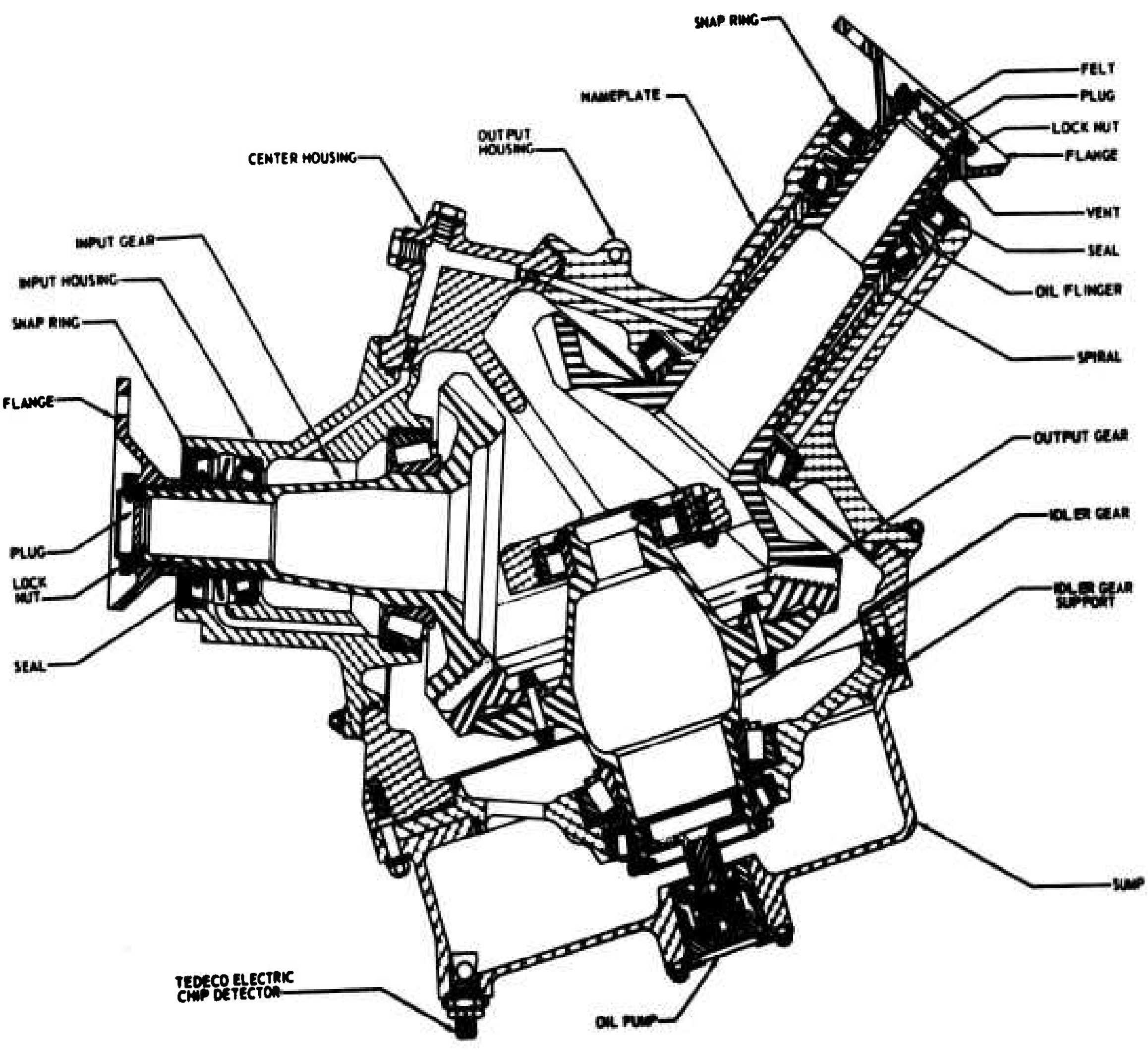

Figure 3. CH-54 Intermediate Gearbox Cross-Sectional View.

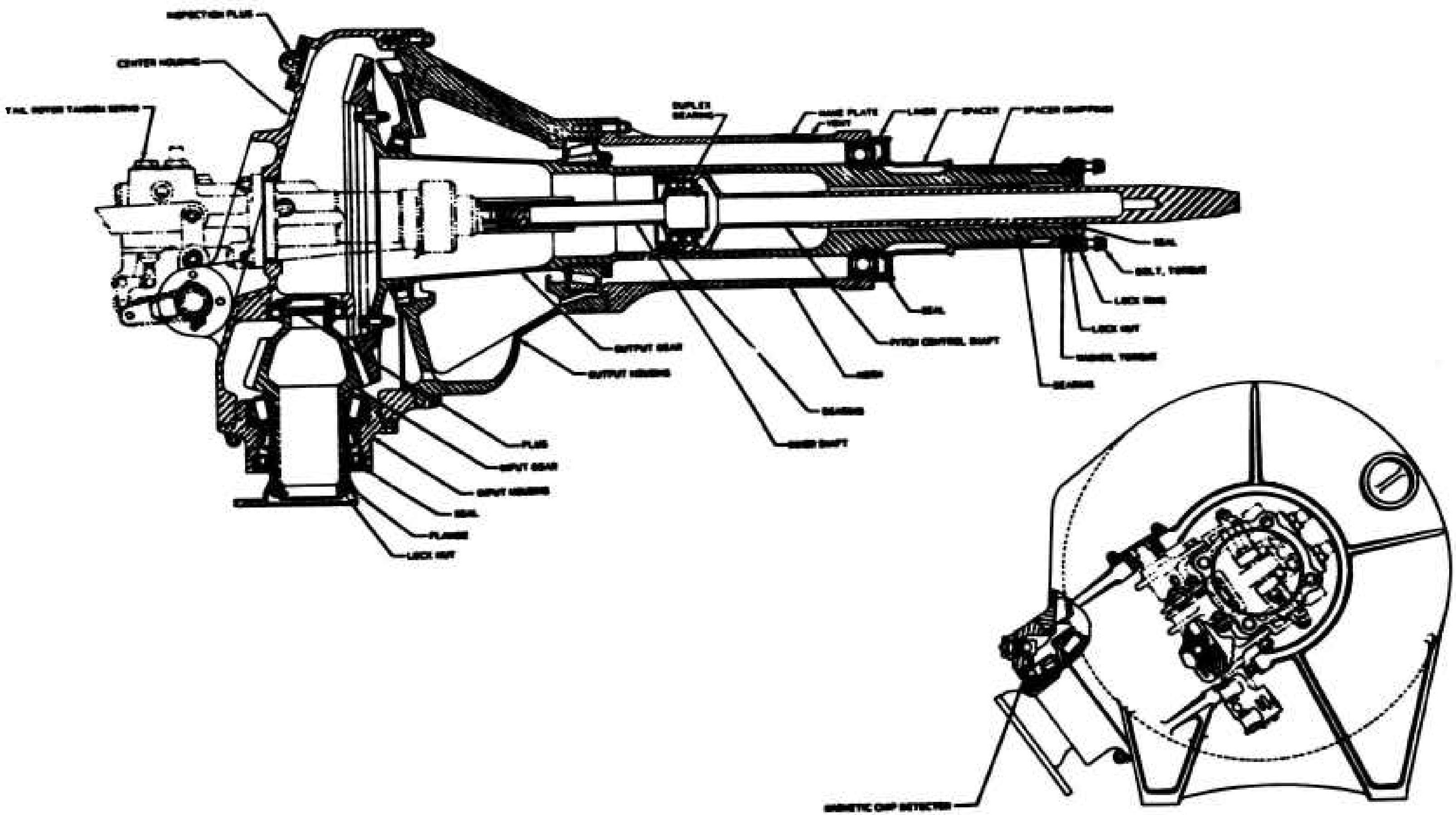

Figure 4. CH-54 Tail Rotor Gearbox Cross-Sectional View.

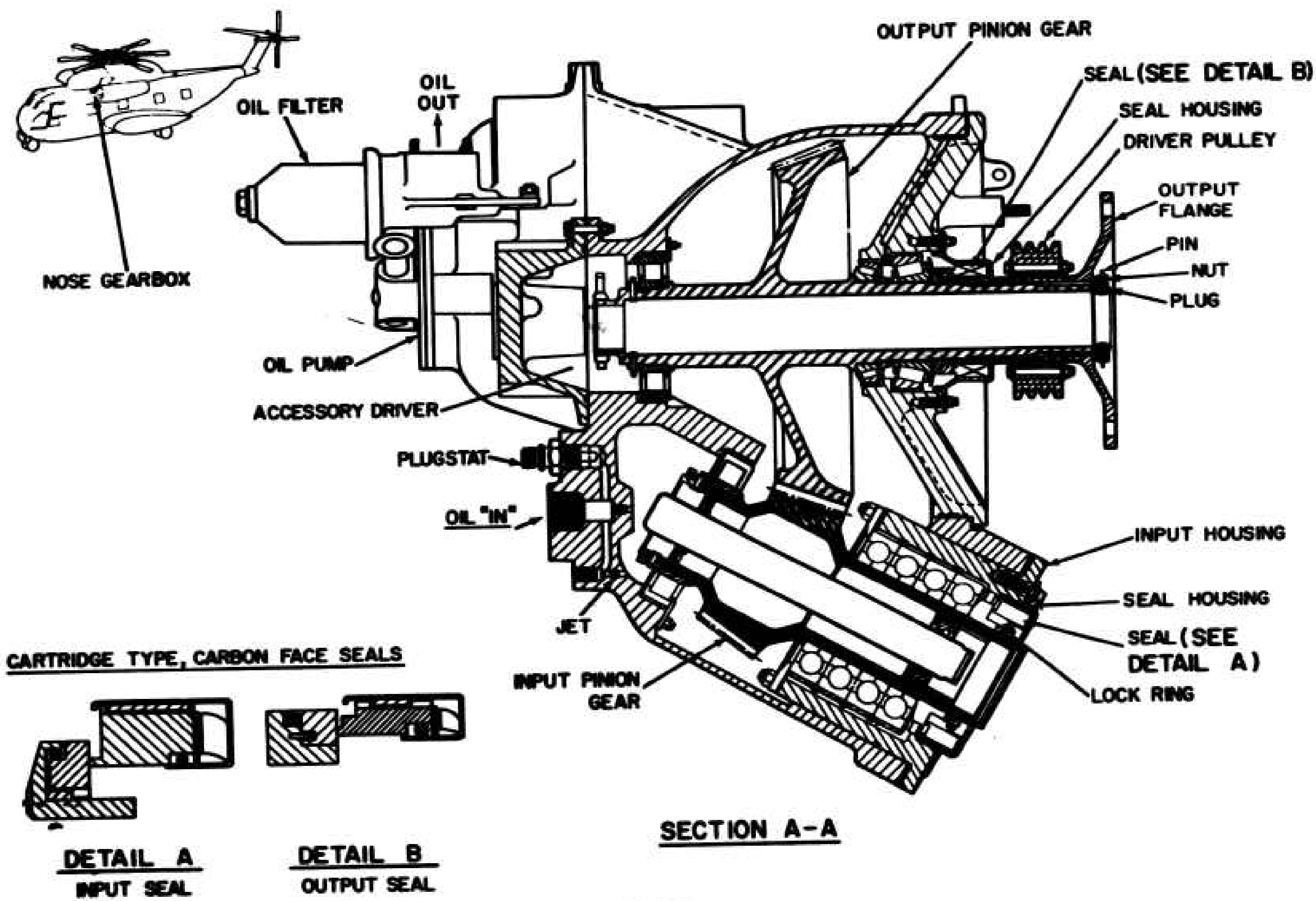

Figure 5. CH-53 Nose Gearbox Assembly - Cutaway (Left-Hand Shown - Right-Hand Opposite).

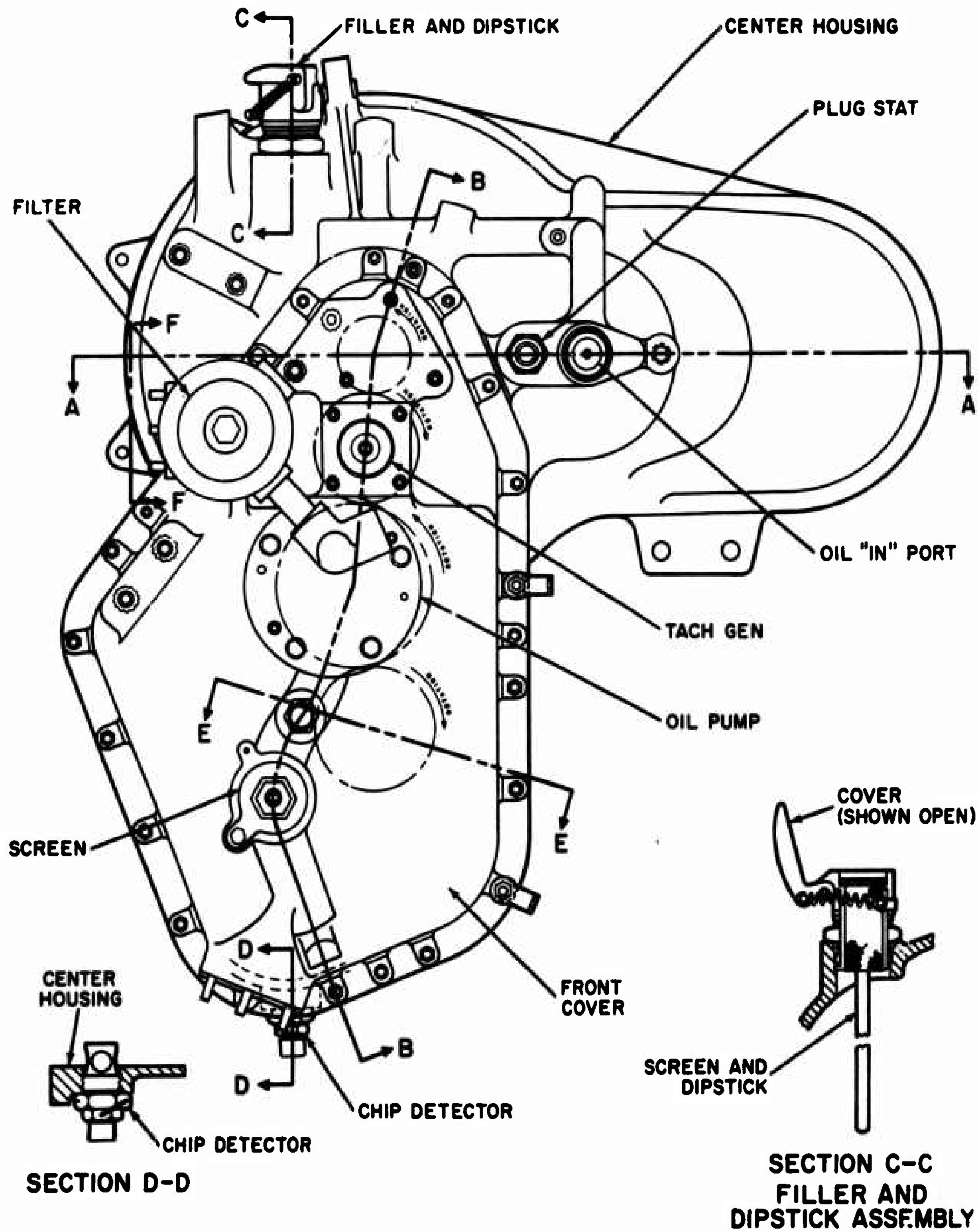

Figure 6. CH-53 Nose Gearbox - Front View (Left-Hand Shown - Right-Hand Opposite).

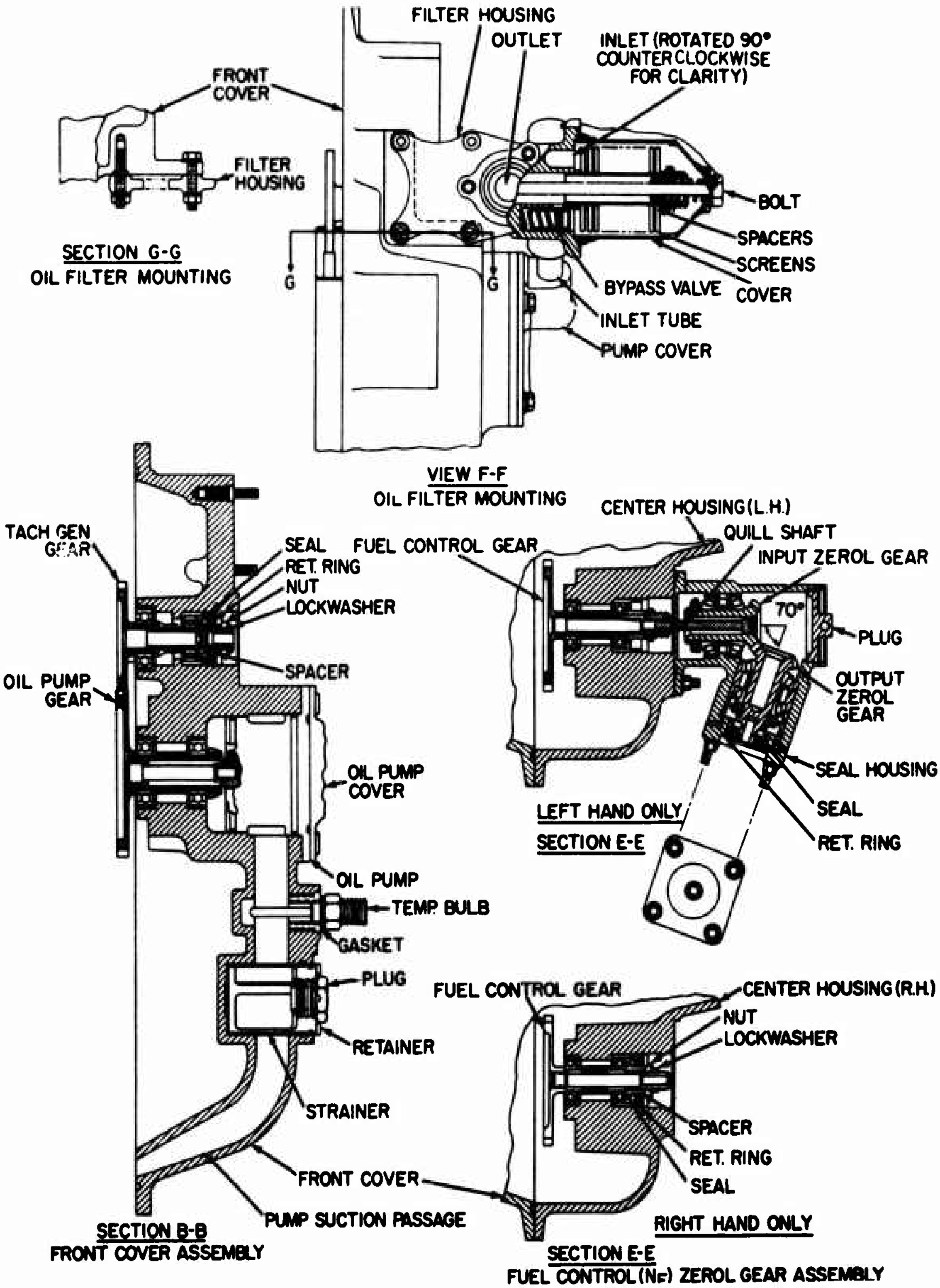

Figure 7. CH-53 Nose Gearbox - Details (Left-Hand Shown - Right-Hand Opposite).

lube pump circulates the oil through an external oil cooler for nose gearbox lubrication and cooling.

1.3.5 CH-53 MAIN GEARBOX

The CH-53D main gearbox couples the two input drive shafts from the nose gearboxes and provides output power for the main rotor, the tail rotor, main gearbox oil cooler and blower, and accessory gearbox during engine operation (see Figures 8 through 11). The two main inputs incorporate a freewheel unit which automatically disengages both engines during auto-rotation or one engine for single-engine operation due to an engine mal-function. The gearbox also drives the first-stage hydraulic pump, a tachometer-generator, and an oil pump that provides lubrication for the gearbox by a wet sump type pressure jet lubrication system. The main oil pump circulates oil from the sump through a filter into an external oil cooler and to the lubrication jets to lubricate gears and bearings of the gearbox. An oil level dipstick is incorporated to measure the oil level. Indicating and warning systems are incorporated for main gearbox oil pressure and oil temperature.

1.3.6 CH-53 ACCESSORY GEARBOX

The accessory gearbox transmits auxilliary power plant power during ground operation to the No. 2 generator, and the utility, winch, and second-stage hydraulic pumps, and transmits main engine power to these same accessories plus the No. 1 generator during rotor operation (see Figures 12 and 13). The gearbox consists of a front cover and liner, housing and liner, free-wheel unit, APP and accessory drive gears, oil level sight window, oil pressure switch, strainer, and chip detector. An oil monitor is installed at the base of the gearbox. An additional electric chip detector, installed on the oil monitor, detects metal particle contamination from the APP clutch. A plug-stat is installed on the oil monitor for the accessory gearbox oil temperature system. A filter assembly is also installed.

1.3.7 CH-53 INTERMEDIATE GEARBOX

The CH-53 intermediate gearbox transmits torque from the tail drive shaft to the pylon drive shaft, changing the angle of drive (see Figure 14). It consists of an input housing and gear, center housing, and output housing and gear. The center housing has an oil level sight window, a filler plug, an electrical chip detector, and a plugstat. The gearbox is splash lubricated and air cooled.

1.3.8 CH-53 TAIL ROTOR GEARBOX

The CH-53 tail rotor gearbox has a configuration almost identical to that of the CH-54 tail rotor gearbox.

1.4 DATA BASE

The historical data base used for this analysis covers the 1969 - 1971 time frame. Many of the aircraft in the data sample saw action in

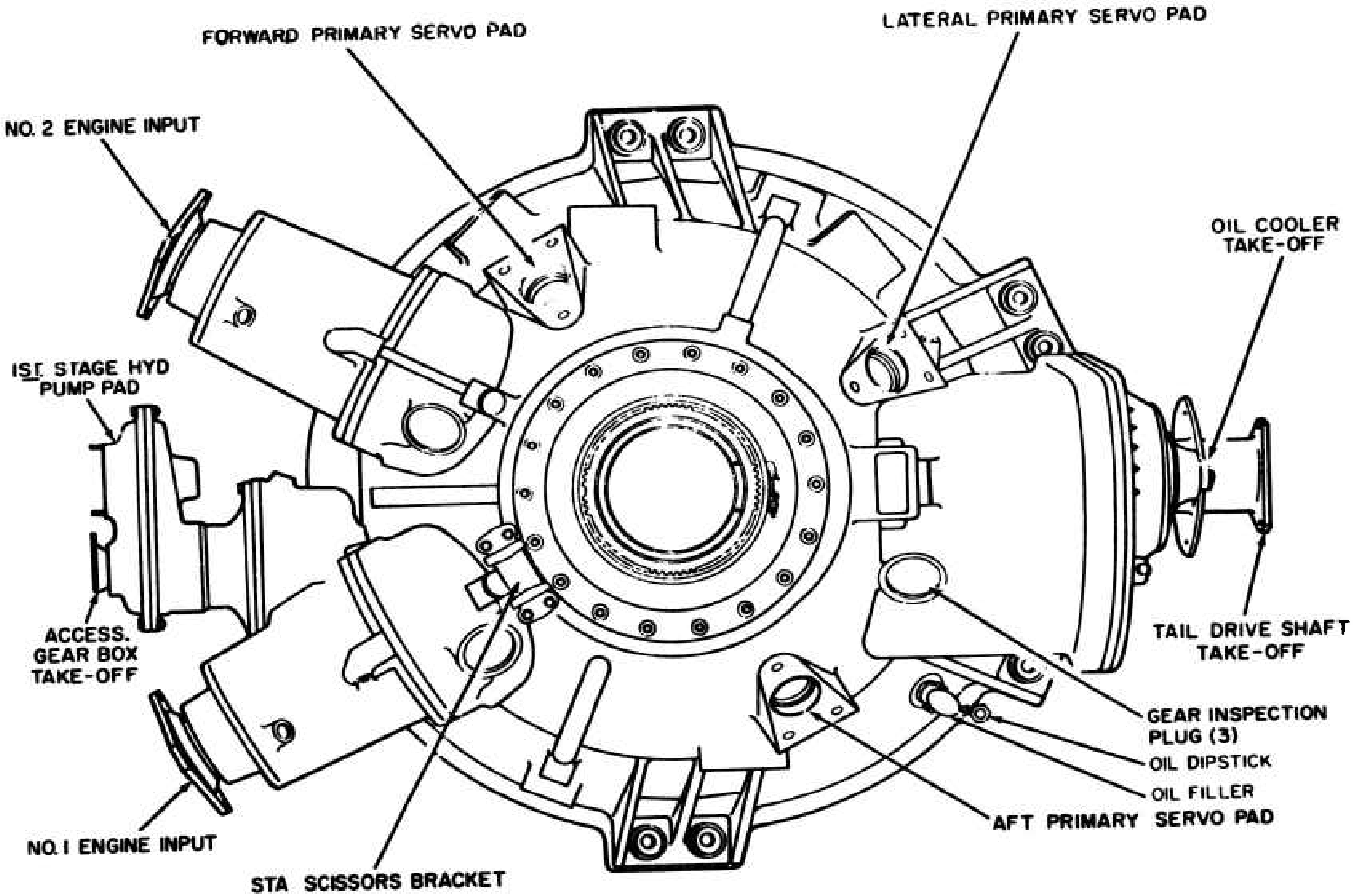

Figure 8. CH-53 Main Gearbox - Top View.

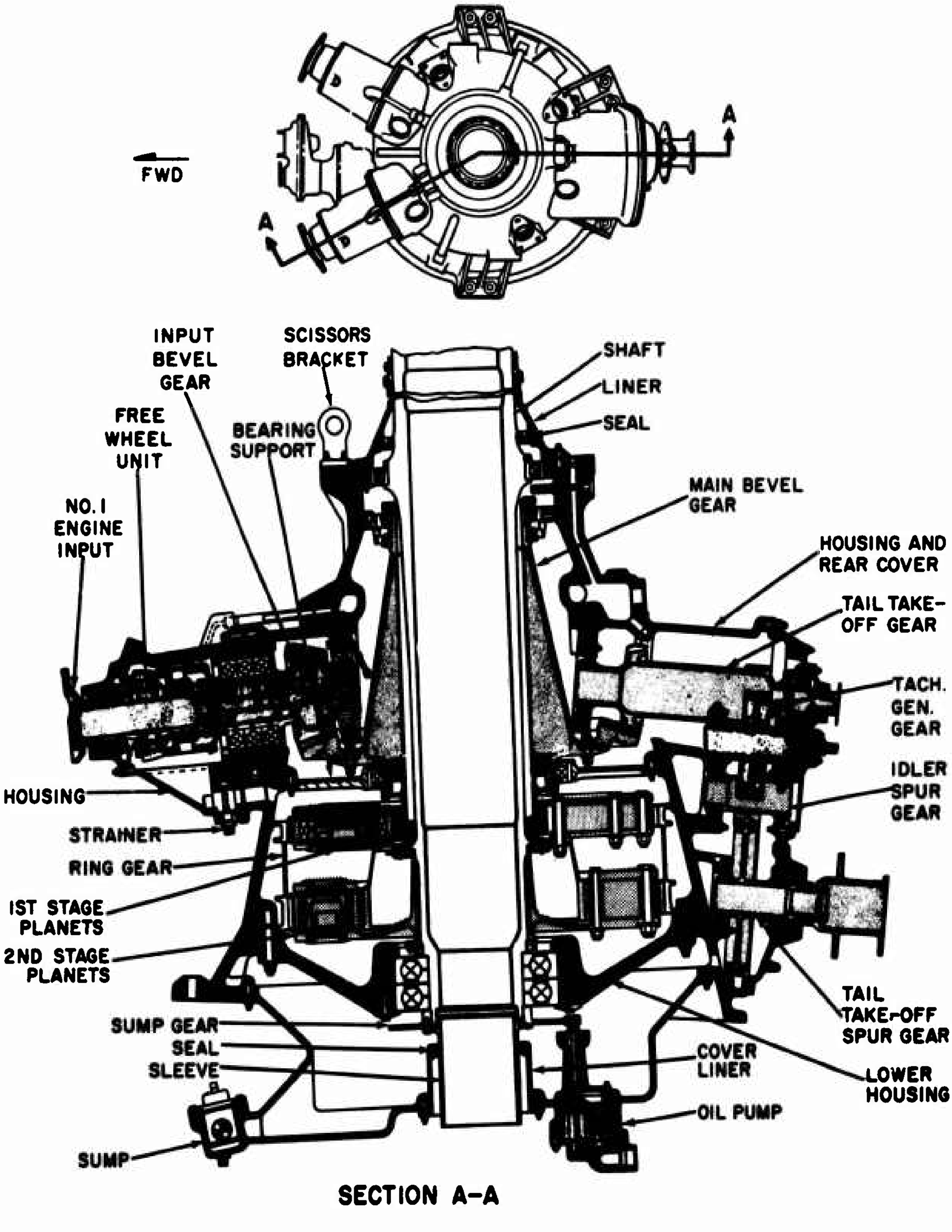

Figure 9. CH-53 Main Gearbox Cutaway.

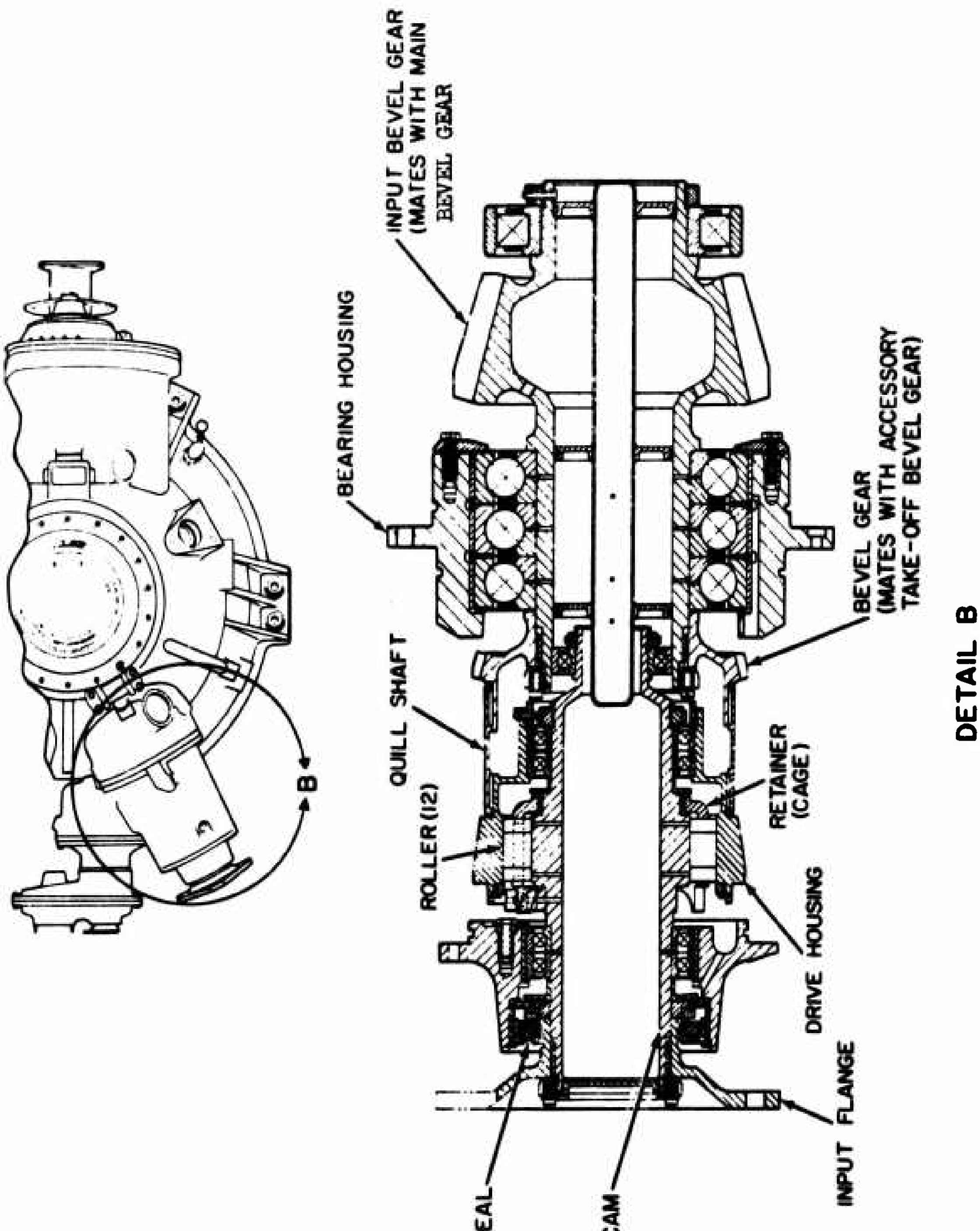

Figure 10. CH-53 Main Gearbox Input Freewheel Unit and Bevel Gear (Left Shown - Right Similar).

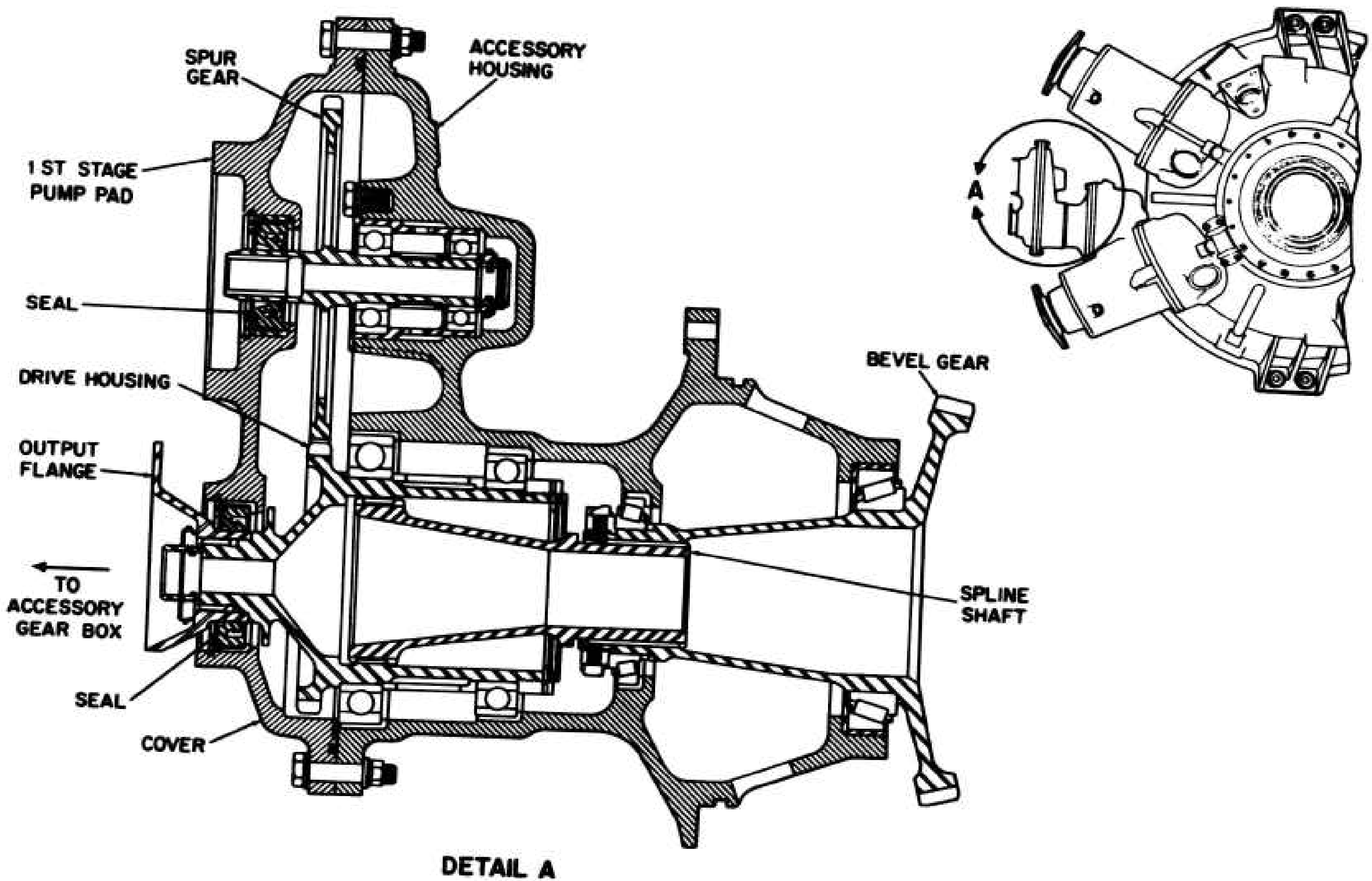

Figure 11. CH-53 Main Gearbox Accessory Takeoff.

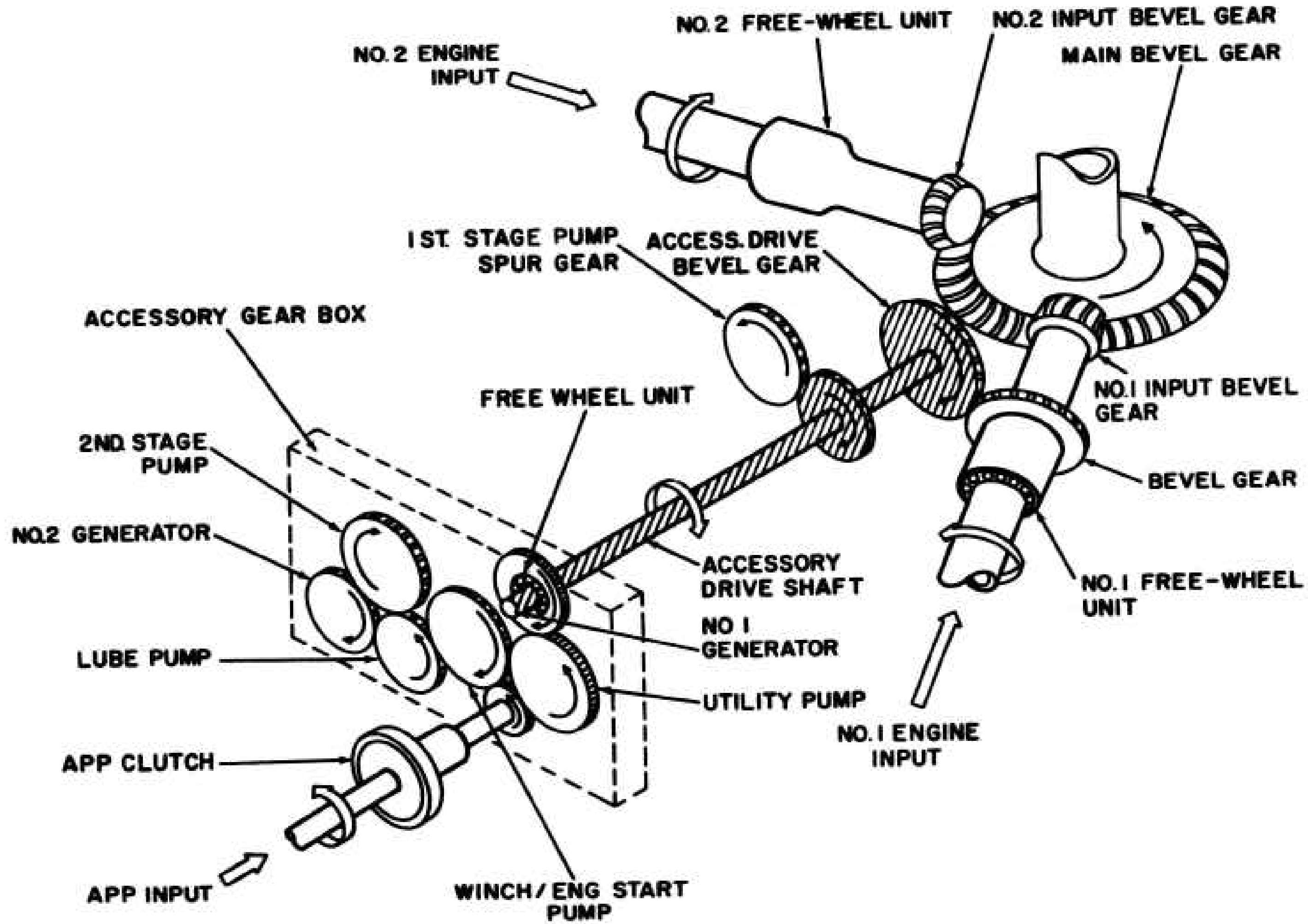

Figure 12. CH-53 Accessory Drive Schematic.

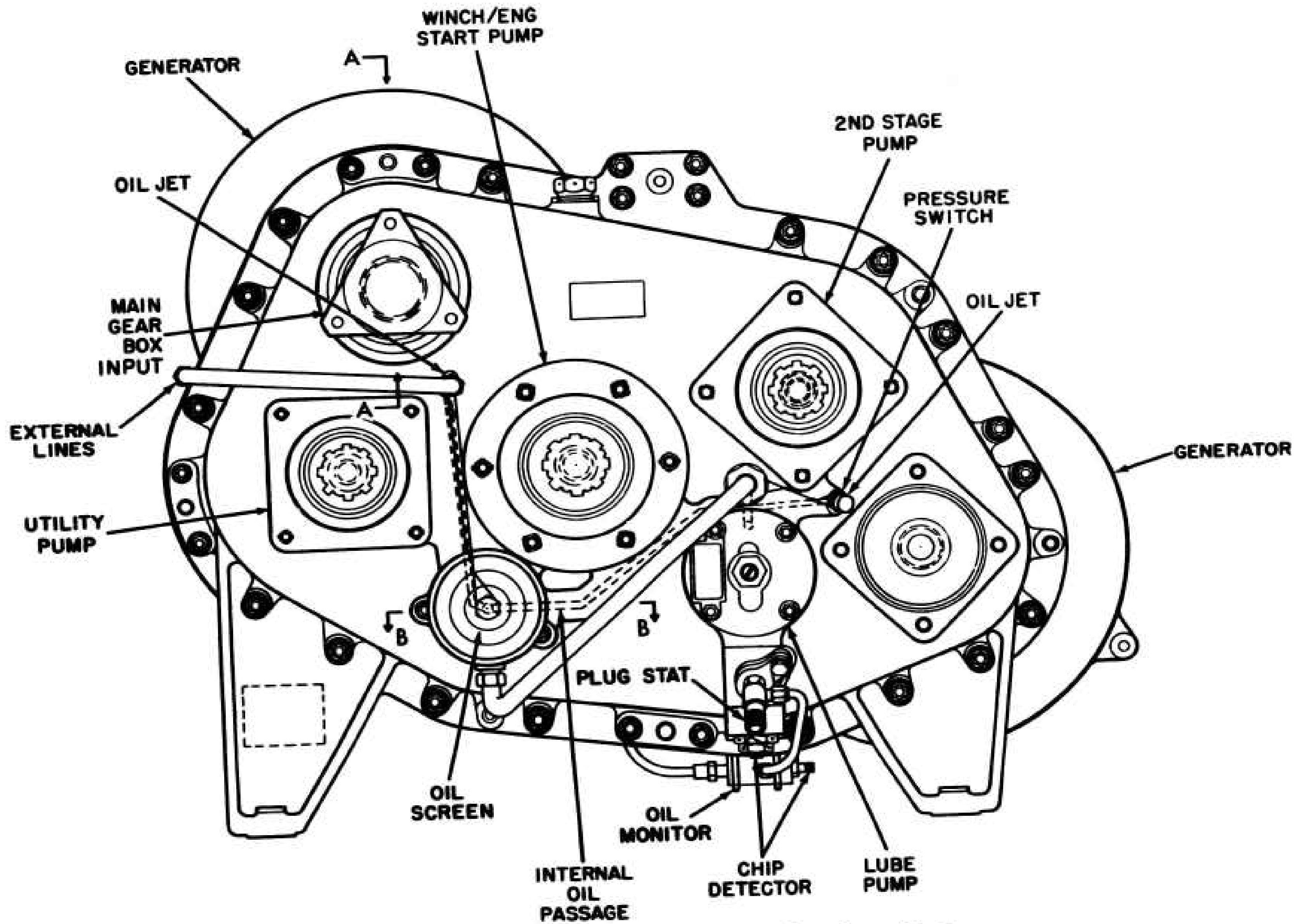

Figure 13. CH-53 Accessory Gearbox Rear View.

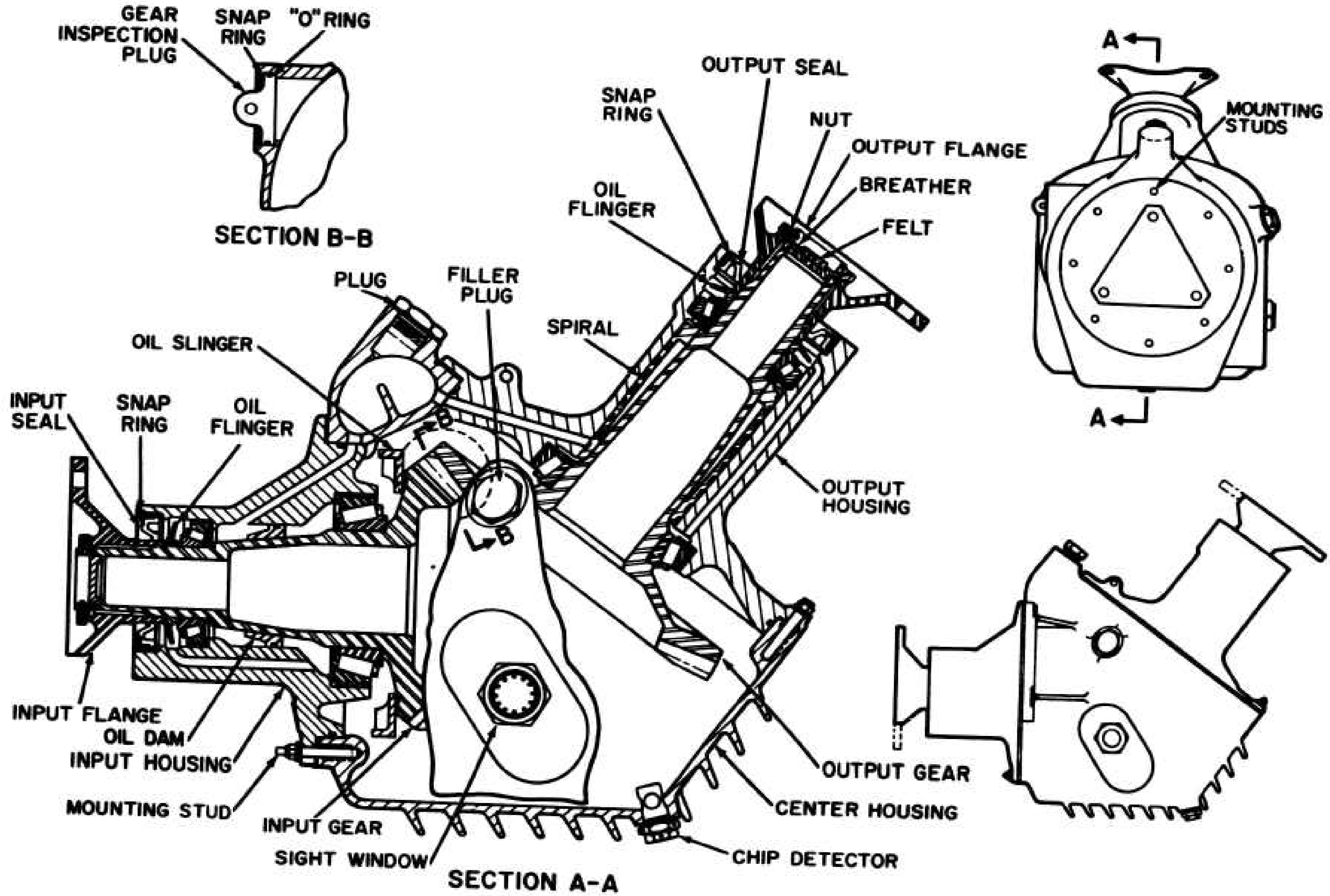

Figure 14. CH-53 Intermediate Gearbox Assembly.

Vietnam. Their gearboxes were subject to overtorque. As a result, generic components such as gears and bearings were subjected to many more cycles of high stress than they might ordinarily have been during peacetime operation.

The CH-54 data consists of approximately 50,000 flight hours of CH-54A field data collected under Contract DAAJ01-68-C-0512, corresponding Disassembly and Inspection Summaries which provide overhaul data, and Sikorsky Field Representative's "Field Service Reports". CH-53 data consists of field data reported by Sikorsky Field Representatives, Sikorsky Field Representative's "Field Service Reports", and overhaul data for the CH-53D between January 1969 and December 1971.

The CH-54 data had the benefit of on-the-spot engineering failure analysis. The majority of the CH-53 data relied on field service findings of depot maintenance. Such data could be misinterpreted since only the best engineering judgement can be applied secondhand. Thus, it is possible that inadvertent biases could have been injected even though every precaution was taken to avoid them.

2.0 STUDY FINDINGS

With minor modifications, the gearboxes studied are suitable for "on-condition". Improvements to the CH-53/54 gearboxes that enhance "on-condition" are discussed in Section 3.0. Current inspection techniques and diagnostic devices are generally adequate in terms of detecting potential safety-of-flight and mission-aborting failure modes. A relatively few key failure modes are significant in affecting gearbox reliability.

2.1 FAILURE MODE AND EFFECT ANALYSIS (FMEA) RESULTS

The worst effect of many gearbox failure modes which is possible considering the impact of maintenance inspections and diagnostics is a mission reliability failure. Many failure modes that are potentially safety-of-flight failures were recategorized due to the beneficial impact of current inspection techniques and diagnostics devices. Many of these are at worst a mission reliability failure. However, field experience reveals that many such failure modes often only result in dynamic component removals.

The FMEA was conducted, as explained in Section 1.2, to define drive system failure modes. The effect on aircraft reliability performance, considering the benefit of maintenance inspections and diagnostic systems, was determined to properly allocate the failure modes that comprise the safety of flight and mission reliability categories. Tables 2 through 9 contain the most serious effects of drive system failure modes on aircraft reliability performance.

Each of the tables indicates the worst effect of generic component failure modes for a particular gearbox. The term generic component indicates a family of gearbox components, for example, spiral bevel gears. The reason for introducing it is that much of the work of estimating hazard functions is predicated on the premise that similar components have identical shapes for their hazard functions. Strictly speaking, this is true only if the applications in the service environment are similar.

Tables 2 through 9 were constructed by indicating the number of generic components in each gearbox which have as their worst effect the category of failure mode indicated by the column heading. The general criteria used to evaluate each mode, as previously indicated, are given in Table 1. Failure modes resulting in the loss of either main rotor power or tail rotor power or all electrical and hydraulic power were categorized as safety-of-flight failures. The criteria for safety-of-flight failure modes employed in this study are somewhat more encompassing than those employed in previously conducted FMEA's. Those failure modes which cause an immediate forced landing but which do not result in injury to the crew or catastrophic loss of the vehicle are not considered as serious as the term safety of flight might imply. Failure modes which activate fault detection systems, such as the chip detector system, were categorized as mission reliability failures. The remaining gearbox failure modes that resulted in gearbox removal were classified as a dynamic component removal failure.

Tables 2 through 9 should not be construed as indicating that many gearbox failures are mission reliability failures. They do indicate, however, that many drive system failures are no more severe than a mission abort.

TABLE 2. CH-54 MAIN GEARBOX GENERIC COMPONENT FAILURE MODES

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Spiral Bevel Gear	Excess Wear	-	10	-
	Spalling	-	10	-
	Scoring	-	10	-
	Tooth Fracture	1	9	-
	Web Crack	2	8	-
Spur Gear	Excess Wear	-	41	-
	Spalling	-	41	-
	Scoring	-	41	-
	Tooth Fracture	28	13	-
	Web Crack	28	13	-
Spline	Wear	3	31	-
Ball Bearing	Cage Fracture	1	21	-
	Spalling	-	22	-
	Smearing	-	22	-
	Excess Wear	-	22	-
Roller Bearing	Cage Fracture	29	17	-
	Spalling	-	46	-
	Smearing	-	46	-
	Excess Wear	-	46	-
Tapered Roller Bearing	Cage Fracture	4	10	-
	Spalling	-	14	-
	Smearing	-	14	-
	Excess Wear	-	14	-
Lock Ring	Fracture	-	13	-
Bearing Retainer	Crack, Shear	-	32	-

TABLE 2. CH-54 MAIN GEARBOX GENERIC COMPONENT FAILURE MODES (Continued)

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Flange	Crack	1	-	2
Shaft	Fracture	2	2	1
	Cracking	-	3	1
	Spline Wear	-	3	-
	Square Hole Enlargement	-	-	1
Thrust Washer	Excess Wear	-	59	-
Freewheel Unit Cam	Spline Wear	-	3	-
	Spring Seat Fracture	-	3	-
Freewheel Unit Cage	Excess Wear	-	3	-
	Fracture	-	3	-
Freewheel Unit Rollers	Spalling	-	68	-
	Excess Wear	-	68	-
	Brinelling	-	68	-
Spring	Fracture	-	6	-
Nut	Loose	2	118	-
"O" Ring	Leaking (External)	-	2	24
	(Internal)	-	4	-
Shaft Seal	Leakage	-	8	5
Lube Pump	Low Oil Pressure	1	1	-
Housing	Crack	-	-	10
Plate Assembly	Crack	2	-	-

TABLE 3. CH-54 INTERMEDIATE GEARBOX GENERIC COMPONENT FAILURE MODES

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Spiral Bevel Gear	Excess Wear	-	3	-
	Spalling	-	3	-
	Scoring	-	3	-
	Tooth Fracture	-	3	-
	Crack	4	-	-
Roller Bearing	Cage Fracture	1	-	-
	Spalling	-	1	-
	Smearing	-	1	-
	Excess Wear	-	1	-
Tapered Roller	Cage Fracture	4	2	-
	Spalling	-	6	-
	Smearing	-	6	-
	Excess Wear	-	6	-
Spline	Wear	2	2	-
Nuts	Loose	1	3	-
Lip Seals	Leakage	-	2	-
"O" Rings	Leakage	-	7	-
Gear Shaft Bolts	Shear	-	12	-
Clip Retainer	Fracture	1	-	-
Snap Ring	Fracture	-	1	-
Oil Pump	No Output Pressure	1	-	-
Housing	Crack	4	-	-

TABLE 4. CH-54 TAIL ROTOR GEARBOX GENERIC COMPONENT FAILURE MODES

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Spiral Bevel Gear	Excess Wear	-	2	-
	Spalling	-	2	-
	Scoring	-	2	-
	Tooth Fracture	-	2	-
	Crack	2	-	-
Ball Bearing	Cage Fracture	1	-	-
	Spalling	-	1	-
	Smearing	-	1	-
	Excess Wear	-	1	-
Tapered Roller Bearing	Cage Fracture	2	2	-
	Spalling	-	4	-
	Smearing	-	4	-
	Excess Wear	-	4	-
Roller Bearing	Cage Fracture	1	-	-
	Spalling	-	1	-
	Smearing	-	1	-
	Excess Wear	-	1	-
Bearing Retainer	Fracture	1	-	-
Spline	Wear	3	-	-
Shaft	Crack	1	-	-
Nut	Loose	2	2	12
"O" Ring	Leakage	-	8	-
Lip Seals	Leakage	-	3	-
Pitch Control Shaft **Antirotation** Groove	Fretting	1	-	-
Housing	Crack	3	-	-

TABLE 5. CH-53 NOSE GEARBOX GENERIC COMPONENT FAILURE MODES

Generic Component	Failure Mode	Number of Safety of Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Spiral Bevel Gear	Excess Wear	-	2	-
	Spalling	-	2	-
	Scoring	-	2	-
	Tooth Fracture	-	2	-
	Crack	-	2	-
Spur Gear	Excess Wear	-	4	-
	Spalling	-	4	-
	Scoring	-	4	-
	Tooth Fracture	-	4	-
	Crack	-	4	-
Ball Bearing	Cage Fracture	-	10	-
	Spalling	-	10	-
	Smearing	-	10	-
	Excess Wear	-	10	-
Roller Bearing	Cage Fracture	-	2	-
	Spalling	-	2	-
	Smearing	-	2	-
	Excess Wear	-	2	-
Tapered Roller Bearing	Cage Fracture	-	2	-
	Spalling	-	2	-
	Smearing	-	2	-
	Excess Wear	-	2	-
Spline	Wear	-	3	-
Nut	Loose	-	7	-
Bearing Retainer	Fracture	-	3	-
Shaft Seal	Leakage	-	4	-
"O" Ring Seals	Leakage	-	30	-
Flange (Drive Shaft)	Spline Fretting	-	1	-
Pulley Driver	Sheared	-	1	-

TABLE 5. CH-53 NOSE GEARBOX GENERIC COMPONENT FAILURE MODES (Continued)

Generic[a] Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Fan Pulley	Wear	-	1	-
Square Aperture	Enlargement	-	2	-
Quill Shaft	Spline Fretting	-	1	-
	Cracking	-	1	-
Lube Pump	Low Flow	-	1	-
Housing	Crack	-	-	4
Oil Jets	Clogging	-	7	-
	Enlargment	-	7	-
Lube Tube	Clogging	-	1	-
	Enlargement	-	1	-
Spiral Bevel Gear	Excess Wear	-	2	-
	Spalling	-	2	-
	Scoring	-	2	-
	Tooth Fracture	-	2	-
	Cracking	-	2	-
Spline	Wear	-	2	-
Tapered Roller Bearing	Cage Fracture	-	4	-
	Spalling	-	4	-
	Smearing	-	4	-
	Excess Wear	-	4	-
Nut	Loose	-	2	-
Quill Shaft	Spline Fretting	-	1	-
	Cracking	-	1	-

[a]An additional bevel gear set was added to the left nose gearbox to change the right-facing speed cable takeoff to a left-facing takeoff to mate with the engine speed cable originating from the left side of the engine.

TABLE 6. CH-53 MAIN GEARBOX GENERIC COMPONENT FAILURE MODES

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Spiral Bevel Gear	Excess Wear	-	6	-
	Spalling	-	6	-
	Scoring	-	6	-
	Tooth Fracture	1	5	-
	Crack	3	3	-
Spur Gear	Excess Wear	-	29	-
	Spalling	-	29	-
	Scoring	-	29	-
	Tooth Fracture	2	27	-
	Crack	26	3	-
Ball Bearing	Cage Fracture	4	14	-
	Spalling	-	18	-
	Smearing	-	18	-
	Excess Wear	-	18	-
	Brinelling	-	6	-
Roller Bearing	Cage Fracture	25	2	-
	Spalling	-	27	-
	Smearing	-	27	-
	Excess Wear	-	27	-
Tapered Roller Bearing	Cage Fracture	6	1	-
	Spalling	-	7	-
	Smearing	-	7	-
	Excess Wear	-	7	-
Spline	Wear	4	20	-
Bearing Retainer	Crack, Shear	-	25	-
Thrust Washer	Excess Wear	-	42	-

TABLE 6. CH-53 MAIN GEARBOX GENERIC COMPONENT FAILURE MODES (Continued)

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
"O" Ring	Leakage (External)	-	34	-
	(Internal)	-	4	-
Shaft Seal	Leakage	-	8	1
Flange	Crack	1	3	-
FWU Housing	Crack	-	2	-
FWU Rollers	Spalling	-	24	-
	Excess Wear	-	24	-
	Brinelling	-	24	-
FWU Cage	Excess Wear	-	2	-
	Fracture	-	2	-
Spring	Fracture	-	-	4
Shaft	Fracture	2	3	-
Housing	Crack	3	2	4
Plate Assembly	Crack	2	-	-
Lube Pump	Oil Pressure Lost	-	1	-

TABLE 7. CH-53 ACCESSORY GEARBOX GENERIC COMPONENT FAILURE MODES

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Spur Gear	Excess Wear	-	7	-
	Spalling	-	7	-
	Scoring	-	7	-
	Tooth Fracture	-	7	-
	Crack	-	7	-
Ball Bearing	Cage Fracture	-	11	-
	Spalling	-	11	-
	Smearing	-	11	-
	Excess Wear	-	11	-
Roller Bearing	Cage Fracture	-	5	-
	Spalling	-	5	-
	Smearing	-	5	-
	Excess Wear	-	5	-
Spline	Wear	-	8	-
Nut	Loose	-	10	-
Lock Ring	Fracture	-	14	-
Shaft Oil Seal	Leakage	-	6	-
"O" Ring	External Leakage	-	9	-
FWU Roller	Spalling	-	12	-
	Excess Wear	-	12	-
	Brinelling	-	12	-
FWU Cage	Excess Wear	-	1	-
	Fracture	-	1	-
Thrust Washer	Wear	-	2	-
Spring	Fracture	-	2	-

TABLE 7. CH-53 ACCESSORY GEARBOX GENERIC COMPONENT FAILURE MODES (Continued)

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Shaft	Cracking	-	1	-
Lube Pump	Low Pressure	-	1	-
Oil Jet	Clogging	-	3	-
	Enlargement	-	3	-
Housing	Crack	-	2	-

TABLE 8. CH-53 INTERMEDIATE GEARBOX GENERIC COMPONENT FAILURE MODES

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Spiral Bevel Gear	Excess Wear	-	2	-
	Spalling	-	2	-
	Scoring	-	2	-
	Tooth Fracture	-	2	-
	Crack	3	-	-
Tapered Roller Bearing	Cage Fracture	-	4	-
	Spalling	-	4	-
	Smearing	-	4	-
	Excess Wear	-	4	-
Spline	Excess Wear	2	-	-
Nut	Loose	-	2	-
"O" Rings	Leakage	-	5	-
Lip Seals	Leakage	-	2	-
Housing	Cracked	3	-	-

TABLE 9. CH-53 TAIL ROTOR GEARBOX GENERIC COMPONENT FAILURE MODES

Generic Component	Failure Mode	Number of Safety-of-Flight Failure Modes	Number of Mission Reliability Failure Modes	Number of Dynamic Component Removal Failure Modes
Spiral Bevel Gear	Excess Wear	-	2	-
	Spalling	-	2	-
	Scoring	-	2	-
	Tooth Fracture	-	2	-
	Crack	2	-	-
Ball Bearing	Cage Fracture	1	-	-
	Spalling	-	1	-
	Smearing	-	1	-
	Excess Wear	-	1	-
Tapered Roller Bearing	Cage Fracture	2	2	-
	Spalling	-	4	-
	Smearing	-	4	-
	Excess Wear	-	4	-
Roller Bearing	Cage Fracture	1	-	-
	Spalling	-	1	-
	Smearing	-	1	-
	Excess Wear	-	1	-
Bearing Retainer	Fracture	1	-	-
Spline	Wear	3	-	-
Shaft	Crack	1	-	-
Nut	Loose	2	2	12
"O" Ring	Leakage	-	8	-
Lip Seals	Leakage	-	3	-
Pitch Control Shaft Antirotation Groove	Fretting	1	-	-
Housing	Crack	3	-	-

The fact that many gearbox failures are not mission aborts can be seen from Table 10. Table 10 indicates the percentage of observed dynamic component removals that were also mission aborts. The term dynamic component removals now includes those failure removals which just resulted in gearbox replacement and those which also resulted in a mission abort. The fact that most gearbox failures do not result in mission aborts indicates the way in which gearbox failure modes propagate. Many failure modes do not suddenly cause catastrophic failure. Bearing spalling, for example, begins as a subsurface crack, which propagates to the surface, causing a small pit. The pits begin to grow in size and in number to where many chips are generated and bearing performance is seriously compromised. The entire process from when chips are first detected to when the gearbox is finally removed can take many missions. In fact, at least one additional hour of gearbox operation is advised by the CH-54 maintenance manual[2] for most cases where the serviceability of a gearbox is doubted due to metal contamination.

[2]Organizational Maintenance Manual, Army Model CH-54B Helicopter, TM 55-1520-217-20-2-1, Headquarters, Department of the Army, 16 April 1973.

TABLE 10. RELATIVE MISSION RELIABILITY OCCURRENCES

Aircraft	Gearbox	Mission Abort Percentage of Dynamic Component Removals
CH-53	Main Gearbox	23
	Nose Gearbox	9
	Accessory Gearbox	2
	Intermediate Gearbox	17
	Tail Rotor Gearbox	3
CH-54	Main Gearbox	16
	Intermediate Gearbox	--[a]
	Tail Rotor Gearbox	--[a]

[a]No mission aborts were recorded in data sample.

2.2 INSPECTION EFFECTIVENESS

The potential effects of many gearbox failure modes are not realized due to the early warning of inspections and diagnostic devices. Tables 11 and 12 summarize the aims, benefits and shortcomings of CH-53 and CH-54 transmission system maintenance inspections and fault detection/warning systems. The CH-53 and CH-54 generally have comparable types of inspection techniques and fault detection/warning systems.

Current inspections and fault detection/warning systems can detect most commonly experienced failures. They can provide a warning for many failure modes which could progress to a potential safety of flight malfunction if they were allowed to degrade for a sufficiently long time. This study has generally assumed that when ample notice of a potential safety-of-flight malfunction is provided by an inspection or fault warning device, recategorization is justified. Examples of this are wear and spalling failures of critical bearings, such as the main thrust bearings (see Figure 2), that are detected by the chip detector to prevent their complete failure; or fretting wear of the pitch change control rod anti-rotation groove that is detected by oil analysis to prevent its complete failure.

Table 13 summarizes the potential safety-of-flight malfunctions that are not detected by current inspections or fault warning systems. These failure modes exhibit virtually a constant hazard function for each of the CH-53/54 gearboxes (see Section 2.4 for a complete discussion of safety-of-flight hazard functions and generic failure modes that comprise the safety-of-flight category). Table 14 summarizes the highest contribution of increasing hazard function failure modes to each gearbox's safety-of-flight hazard function. Generally, the hazard functions of major items can be more effectively reduced by the design improvements recommended in Section 3.1 than by developing a fault warning system. On this basis, current inspections and fault warning systems are adequate for implementing an on-condition maintenance policy.

2.3 EXPERIENCE FAILURE MODE HAZARD FUNCTION

Hazard functions of failure modes with experience data indicate that only a few failure modes would significantly increase if gearboxes were maintained on-condition. Their behavior shows how previous design procedures influenced current gearbox failure modes. They indicate whether current reliability problems reflect design problems and quality control problems or are things that are inherent in the generic component's application.

Three estimates of the hazard function are plotted for each failure mode as follows: (1) the upper 98% confidence limit, denoted on the plot legend as "HU98"; (2) the maximum likelihood estimate, denoted on the plot legend as "HMLE"; (3) the lower 98% confidence limit, denoted on the plot legend as "HL98". The confidence limits apply to the entire

TABLE 11. CH-53 MAINTENANCE INSPECTION AND FAULT DETECTION/WARNING SYSTEM EVALUATION

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
Daily Inspection	Detect common lubrication system failures in all aircraft gearboxes.	1. Significantly reduces the number of potential mission aborts from seal leakage, oil cooler belt wear. 2. Prevents premature gearbox removals due to secondary damage that results when the lubricant is depleted.	Unable to detect those seal failures that result from a sudden increase of internal pressure due to flooding of the seal in flight.
Turnaround Inspection.	Detect significant losses of gearbox lubricant.	1. Significantly reduces the number of potential mission aborts due to seriously degraded seals. 2. Prevents premature gearbox removals due to secondary damage that results when the lubricant is depleted.	Unable to detect those seal failures that result from a sudden increase of internal pressure due to flooding of the seal in flight.
Phase A Inspection	1. Detect tail rotor gearbox leakage, cracks and corrosion of mounting lugs. 2. Detect main gearbox oil cooler leakage, and verify that chip detector is properly installed. 3. Functionally check chip detector system.	1. Positively identifies a completely fractured lug. Significantly reduces the risk of another lug being fractured from increased stresses. 2. Reduces risk of chip detector failures due to faulty installation or due to degradation of installation of mounting hardware or due to electrical malfunctions.	1. Only those double mounting lug failures that might occur within 100 flight hours cannot be detected - a remote event. 2. Visual examination of flanges does not always detect fine cracks that might be present.

TABLE 11. (CONTINUED)

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
	4. Detect cracks in drive shaft flanges, and nicks and dents in drive shaft tubing.	3. Reduces the risk of a crack in a drive shaft from propagating to fracture.	
Phase B Inspection	1. Detect tail rotor gearbox leakage, cracks and corrosion of mounting lugs.	1. Positively identifies a completely fractured lug. Significantly reduces the risk of another lug being fractured from increased stresses.	1. Only those double mounting lug failures that might occur within 100 flight hours cannot be detected - a remote event.
Phase C Inspection	1. Detect cracks, corrosion, and verify mounting hardware security of all gearboxes.	1. Reduces possibility of a housing crack propagating to fracture.	1. Unable to inspect internal housings of main gearbox.
	2. Prevent buildup of foreign material from obstructing chip detectors and oil	2. Maintains complete operational capability of chip detector system.	2. Too infrequent to prevent bearing failures from inadequate lubrication.
	3. Verify integrity of chip detector installation.	3. Reduces possibility of smearing or excessive spalling failures of gearbox bearings due to inadequate lubrication.	
	4. Detect failures within chip detector systems.		
	5. Detect bearing overheating in nose gearbox, accessory gearbox, intermediate gearbox and tail rotor gearbox.	4. Prevents secondary damage resulting from tooth fracture from progressing to complete gear failure.	
Phase D Inspection	1. Detect cracks in airframe support structure of accessory gearbox.	1. Positively identifies a completely fractured mounting of the tail rotor gearbox. Significantly reduces the risk of another lug being fractured from increased stresses.	1. Only those double mounting lug failures of tail rotor gearbox that might occur within 100 flight hours cannot be detected - a remote event.
	2. Detect cracks in accessory gearbox mounts.		

TABLE 11. (CONTINUED)

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
Phase D (Cont'd)	3. Detect cracks in tail rotor gearbox mounting lugs.	2. Reduces possibility of mounting lug fractures in each lug of accessory gearbox.	2. Has no impact on pump spline failures caused by inadequate grease retention.
	4. Detect leakage and corrosion and slippage of tail rotor gearbox.	3. Reduces secondary damage to accessory gearbox from cracks in airframe support.	
	5. Prevent debris accumulation in grease lubricated splines of all hydraulic pumps.	4. Maintains operational capability of accessory gearbox and main gearbox oil hot warning systems.	
	6. Calibrate accessory gearbox and main gearbox oil hot warning systems.	5. Reduces wear rate of grease lucribated hydraulic pump splines.	
Special 28-Day Inspection	Detect main gearbox drive shaft flange cracks.	Reduces possibility of flange fracture.	Fine cracks that cannot be seen visually cannot be detected.
Special 300-Hour Inspection (Oil Sample)	Detect small particle contamination.	Prevents propagation of spline fretting (oil lubricated splines), gear and bearing excess wear, pitch change control rod's anti-rotation groove fretting.	If proper contamination levels are not established, unwarranted gearbox removals will result.
Chip Detector System	Detect generic component failures which result in metal particle contamination.	Provides an early warning for many of the commonly experienced failure modes other than seal leakage and housing cracks.	1. Relies on extensive buildup of small particles for detecting (oil lubricated) spline failures, gear tooth and bearing wear failures. Due to the slow buildup of debris from some failures, they could go undetected by subsequent serviceability check of gearbox.

TABLE 11. (CONTINUED)

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
			2. Unable to detect metal contamination from grease lubricated spline failures. Such splines are outside of the lubrication system.
Oil Pressure Indicating System	1. Detect overpressure from clogging of oil passageways within the main gearbox.	1. Provides an immediate indication of system blockages.	
	2. Detect degradation of lubrication system pressure from losses in the normal back pressure due to significant leakage.	2. Advises pilot of the general health of the seals in the lubrication system.	
	3. Detect low output pressure from pump malfunction.	3. Detects oil pump malfunction.	
Transmission Low Oil Pressure Warning System	Warn the pilot when the oil pressure is too low for normal operation of either the main gearbox, nose gearbox, or accessory gearbox.	1. Detects oil pump malfunction. 2. Detects major leakage within lubrication system of a gearbox.	
Transmission Oil Temperature Indicating Systems	1. Detect degradation in main gearbox oil cooling system. 2. Detect major gear or bearing failure due to overheating in main gearbox.	1. Detects loosening of main gearbox oil cooler fan belts. 2. Advises pilot of the general health of main gearbox cooling system. 3. Prevents possibility of major bearing and gear failure from inadequate oil cooling.	1. Unable to effectively detect local increases in oil temperature from bearing or gear overheating due to location of sensor in sump.

TABLE 11. (CONTINUED)

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
Oil Hot Warning Systems	Warn the pilot that the oil in the nose gearbox or in the main gearbox is too hot for normal operation.	Detects failure of either the nose gearbox or the main gearbox oil cooling system.	

TABLE 11. (CONTINUED)

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
Oil Hot Warning Systems	Warn the pilot that the oil in the nose gearbox or in the main gearbox is too hot for normal operation.	Detects failure of either the nose gearbox or the main gearbox oil cooling system.	

TABLE 12. CH-54 MAINTENANCE INSPECTION AND FAULT DETECTION/WARNING SYSTEM EVALUATION

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
Daily Inspection	1. Detect breather vent obstructions of main gearbox. 2. Detect leakage by main gearbox and oil cooler. 3. Detects nicks and dents of main gearbox drive shafts. 4. Detect leakage of tail rotor gearbox seals. 5. Verify integrity of tail rotor gearbox chip detector installation. 6. Detect any slippage of tail rotor gearbox and cracks on mounting lugs.	1. Provides early detection of seal failures in main gearbox and tail rotor gearbox. 2. Detects possible failure of tail rotor chip detector due to wire chaffing, physical damage, or looseness. 3. Reduces possibility of tail rotor mounting lug fracture and any slippage of gearbox. 4. Prevents corrosion from severely degrading tail rotor gearbox housing.	1. Visual inspection of tail rotor mounting lugs may not detect fine cracks. Those cracks which originate on the mounting lug on the side facing the aircraft skin can not be detected. Furthermore. these cracks, if left to propagate to fracture, may not be visually detected. 2. Does not detect seal leakage of main gearbox or intermediate gearbox. 3. Does not detect overheating from floating grease lubricated splines of engine input.
Intermediate Inspection	1. Detect any metal contamination that may have accrued in the strainer or filter. 2. Verify integrity of main gearbox chip detector. 3. Detect corrosion and cracks in main gearbox mounting frames of the mating flanges. 4. Detect main gearbox oil leakage. 5. Detect loose oil cooler pulley.	1. Prevents secondary damage from gear tooth fractures from progressing to other gear teeth. 2. Prevents gearbox oil from overheating in flight due to oil cooler malfunction. 3. Reduces possibility of corrosion and cracks, causing structural failure of the gearbox housings and mating flanges. 4. Provides warning of imminent seal failure.	1. Will not detect metal particle contamination in smaller than 40 microns. 2. Does not detect cracks of internal main gearbox housings. 3. Fine cracks of main gearbox housings may not be detected.

TABLE 12. (CONTINUED)

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
	6. Detect faulty oil pressure indicator.	5. Provides warning of imminent failure of many generic components that produce large particle metal contamination.	
Periodic Inspection	1. Detect failures in all chip detector systems. 2. Detect metal particle contamination that may have accrued in strainer or filter. 3. Detect cracks and corrosion in all gearbox housings, their mating flanges, mounting structure, and supporting airframe. 4. Detect leakage from any gearbox. 5. Detect loose (below proper torque) mounting bolts. 6. Detect leakage from external lube lines. 7. Detect loose gearbox accessories. 8. Prevent debris from obstructing airflow through radiator core. 9. Detect water contamination in oil.	1. Maintains operational capability of chip detector system. 2. Provides warning of imminent failure of many generic components that produce large particle metal contamination. Secondary damage is prevented from progressing to additional failures. For example, tooth fracture of one gear tooth is prevented from progressing to failure (fracture) of an adjacent tooth. 3. Reduces the possibility that cracks and corrosion will lead to structural failure of gearbox housing and mating flanges. 4. The possibility of mounting bolt fractures from fatigue that results from their being loose is reduced. 5. Provides early warning of seal failures of gearbox and external lubrication lines. 6. Prevents fatigue failure to attaching hardware of gearbox accessories.	1. Visual inspection of gearbox housings and mounting lugs may detect fine cracks or cracks that originate at mounting face. 2. Does not detect metal particle contamination smaller than 40 microns.

TABLE 12. (CONTINUED)

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
25-Hour Oil Sample	1. Detect small particle metal contamination.	1. Detects fretting wear failures of oil lubricated splines, pitch change control shaft antirotation groove, square apertures, and wear failures of bearings and gears.	1. If proper contamination levels are not established, unwarranted gearbox removals will result.
Chip Detector System	1. Detect generic component failures which result in metal particle contamination.	1. Provides an early warning for many of the commonly experienced failure modes other than seal leakage and housing cracks.	1. Relies on extensive buildup of small particles for detecting (oil lubricated) spline failures, gear tooth and bearing wear failures. Due to the slow buildup of debris from some failures, they could go undetected by subsequent serviceability check of gearbox. 2. Unable to detect metal contamination from grease lubricated spline failures. Such splines are outside the lubrication system.
Main Gearbox Oil Pressure Indicating System	1. Detect overpressure from clogging of oil passageways within the main gearbox. 2. Detect degradation of lubrication system pressure from losses in the normal back pressure due to significant leakage. 3. Detect low output pressure resulting from pump malfunction.	1. Provides an immediate indication of system blockages. 2. Advises pilot of the general health of seals in lubrication system. 3. Detects oil malfunction.	

TABLE 12. (CONTINUED)

Inspection, Diagnostic System	Aim	Benefits	Shortcomings
Transmission Low Oil Pressure Warning System (Main Gearbox and Intermediate Gearbox)	1. Warn pilot when the oil pressure is too low for normal operation.	1. Detects oil pump malfunction. 2. Detects major leakage within lubrication system of the gearbox.	
Main Gearbox Oil Temperature Indicating System	1. Detect degradation in transmission oil cooling system. 2. Detect major gear or bearing failure due to overheating.	1. Detects loosening of main gearbox oil cooler fan belts. 2. Advises pilot of the general health of the cooling system. 3. Prevents possibility of major bearing and gear failures from inadequate oil cooling.	1. Unable to effectively detect local increases in oil temperature from bearing or gear overheating due to location of sensor in sump.

TABLE 13. MALFUNCTIONS NOT DETECTED BY CURRENT MAINTENANCE INSPECTIONS AND FAULT WARNING SYSTEMS

Generic Component(s)	Failure Mode
Spiral Bevel Gear, Spur Gear	Web/Shaft Fracture
Ball Bearing, Roller Bearing, Tapered Roller Bearing	Cage Fracture[a]
Shaft	Fracture
Internal Gearbox Housing	Fracture
Grease Lubricated Splines	Wear, Fretting
Nuts	Loose[b]
Bearing Retainer	Fracture
Upper/Lower Planetary Plate Assembly	Fracture
Mounting Lug or Flange	Fracture[c]

[a] Fault detection sensors warn of impending cage fracture from lubrication failure or secondary damage from metal contamination.

[b] Chip detector indicates secondary damage.

[c] Fine cracks or those cracks which occur between airframe and gearbox mounting may not be visually detected.

TABLE 14. SIGNIFICANT POTENTIAL SAFETY-OF-FLIGHT FAILURE MODES

Aircraft	Gearbox	Generic Component Failure Mode[a]	Percentage Contribution to Gearbox Hazard Function[b]
CH-54	Main	Spline Fretting, Wear	67
	Intermediate	Spline Fretting, Wear	15
		Nuts Loose	8
		Housing Crack	1
	Tail Rotor	Spline Fretting, Wear	46
		Housing Crack	41
CH-53	Main	Spline Fretting, Wear	12
		Housing Crack	4
	Intermediate	Housing Crack	1
		Spline Fretting, Wear	84
	Tail Rotor	Housing Crack	25
		Spline Fretting, Wear	42

[a]Only failure modes with increasing hazard functions are listed.

[b]At 5000 hours.

hazard function, not just to the shape and size parameters. As a result, the statistical significance associated with a hazard function should not be construed as indicating the statistical significance associated with the size and shape parameters of the Weibull distribution.

Representative hazard function plots are shown in the following section.

2.3.1 BEARINGS

Bearings in this study were divided into three generic types: (1) ball bearings, (2) cylindrical roller bearings, and (3) tapered roller bearings. The failure modes predicted for each bearing were cage fracture, smearing, pitting or spalling, and excessive wear. Pitting and spalling failures usually originate as subsurface cracks, which result from Hertzian stresses that occur between the rolling elements and the inner race. These propagate to the surface and form pits. Excess wear represents surface damage resulting either from intermittent skidding of the rolling elements or from abrasion caused by foreign particles present in the oil. Smearing usually results from the lubricant being unable to sustain a film, which causes an alternating welding and tearing of the rolling elements.

Figures 15 through 19 show some hazard function of CH-53/54 bearing failures that have been experienced. Figure 15 is the hazard function for cage fracture failures that were experienced by the CH-53 nose gearbox's main thrust bearings (see Figure 5). The shape of the hazard function suggests that the cage is subject to fatigue. Usually cages are overdesigned in terms of stresses that are applied in normal operation. As a result, infinite life and constant hazard functions are expected. However, failures of the outer race bearing retainer, the bearing retention nut, and its lock-nut that were experienced on other occasions by the nose gearbox suggest other failure mechanisms may be responsible. While the data indicates that fracture of machined cages were responsible for gearbox failure, it is suspected that either debris from inner race rotation or machining of the cage by the outer race bearing retainer is the true failure mechanism.

Figures 16 through 18 show the hazard functions for pitting and spalling failures. They clearly represent different failure mechanisms. The shape of the hazard function shown in Figure 16 is what should be expected when quality control and lubrication are adequate for AISI 52100 bearings. This result is confirmed by the hazard function of the CH-54 intermediate gearbox tapered roller bearings for spalling failures ($\beta = 1.21$) and by testing done outside of Sikorsky, such as by Chevalier et al.[3]

[3]Chevalier, J. L., Zaretsky, E. V., Parker, R. J., "A New Criterion for Predicting Rolling Element Fatigue Lives of Through Hardened Steels", Journal of Lubrication Technology, July 1973.

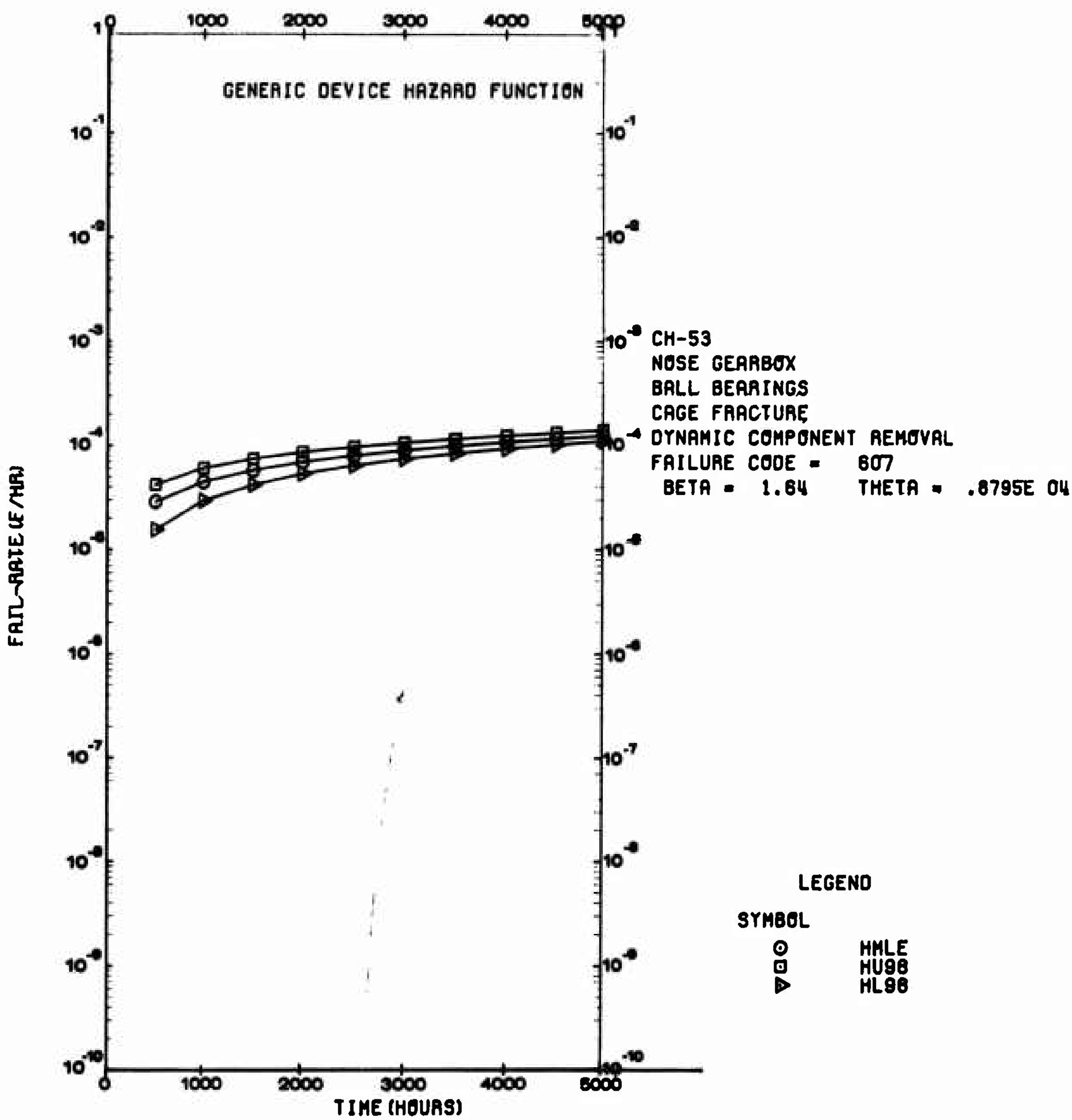

Figure 15. Bearing Cage Fracture Hazard Function.

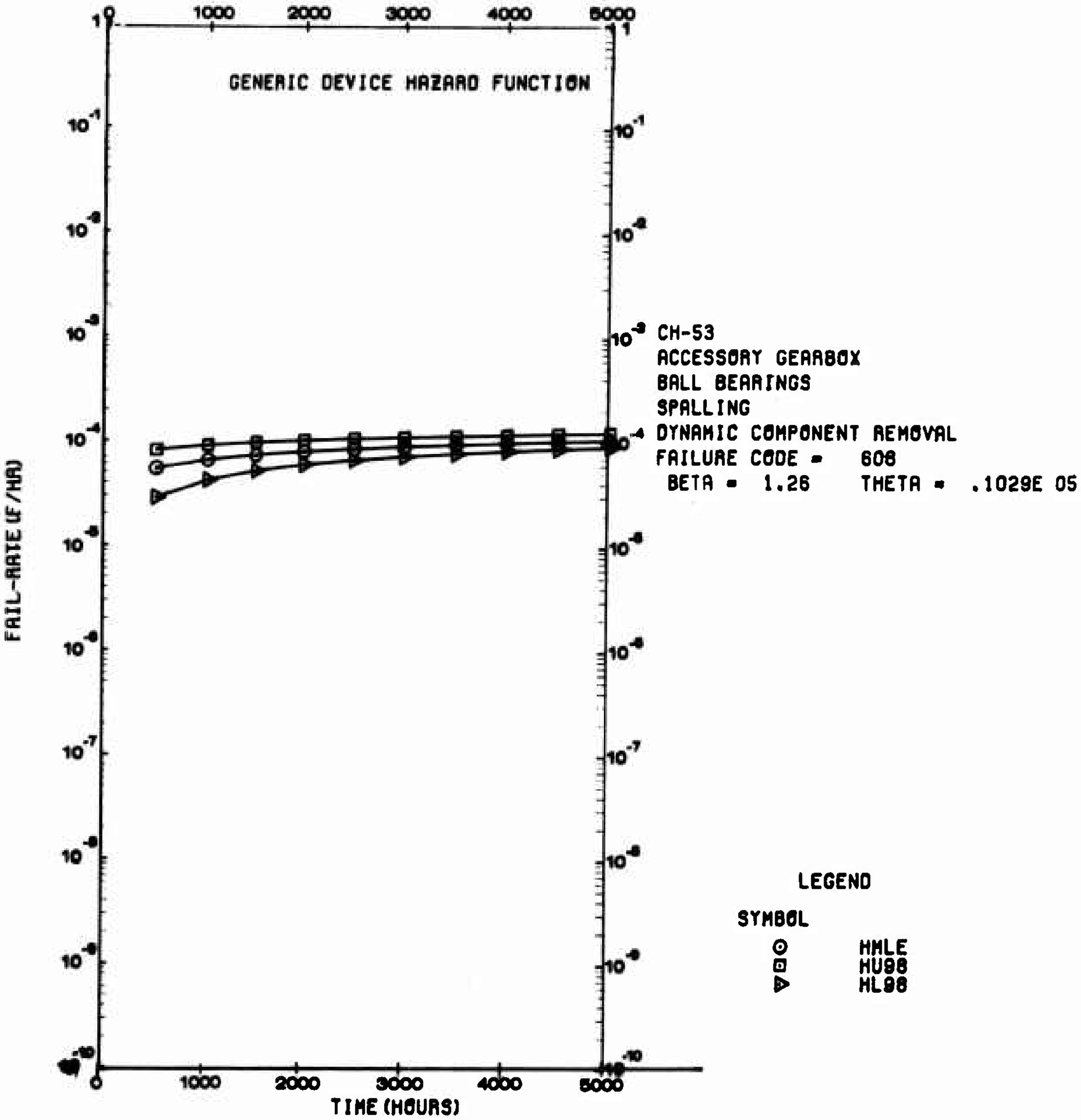

Figure 16. Bearing Spalling Hazard Function.

The shape of the hazard function shown in Figure 17 is indicative of a quality control problem. While the exact mechanism could not be determined from the data, the fact that the problem area can be defined is useful if product improvement is desired.

Figure 18 is indicative of spalling failures that result from minimal lubrication. Similar results were observed for CH-53 intermediate gearbox tapered roller bearings. The major problem shown in Figure 18 is attributable to marginal lubrication of the planetary roller bearings. The bearings operate at temperatures much higher than are generally recommended for AISI 52100 steel bearings. The high operating temperatures cause a reduction in the material hardness, which in turn aggravates spalling. The effect of operating temperature on 52100's hardness is well documented by Chevlier et al. As a result, Figure 18 shows that either a better lubrication method or a material capable of operating higher temperatures is needed.

Figures 16 and 18 demonstrate that even when bearings are made from the same materials and processes, the specific application must be evaluated before estimating hazard function parameters.

Figure 19 is representative of the few smearing failures that have been experienced. As can be seen from Figure 19, β's are typically close to unity for this mode, while the θ's are larger than those for spalling. While the data did not allow identification of the specific mechanism, it is suspected that they are related to lubrication problems known to exist for input tapered roller bearing.

None of the failure modes discussed affect safety-of-flight. As a result, no corrective action is essential to implement on-condition maintenance. However, corrective action is desirable to improve product reliability for the failure modes shown in Figure 18. Corrective action was taken for the failure modes depicted in Figures 15 and 19 during the design of RH-53D helicopter. Section 3 will further discuss what corrective action is desirable for implementing on-condition maintenance.

2.3.2 GEARS

Relatively few failures of gears have resulted in there being no significant hazard functions for thos CH-53/54 generic modes with experience data. Tooth wear and tooth fracture were the only failure modes recorded in this study's data bank.

Figures 20 and 21 are hazard functions for wear failures that were observed on accessory gearbox spur gears and nose gearbox spiral bevel gears. While they represent hazard functions of different types of gears, it is interesting to note that both have approximately the same shape. The fact that both hazard functions are increasing is indicative of cumulative surface damage. Many wear mechanisms could be responsible, such as corrosion, abrasion, adhesion, and delamination.[4] Without examining the gears, it is

[4]Suh, N. P., "The Delamination Theory of Wear", WEAR, Volume 25, 1973, pp. 111 - 124.

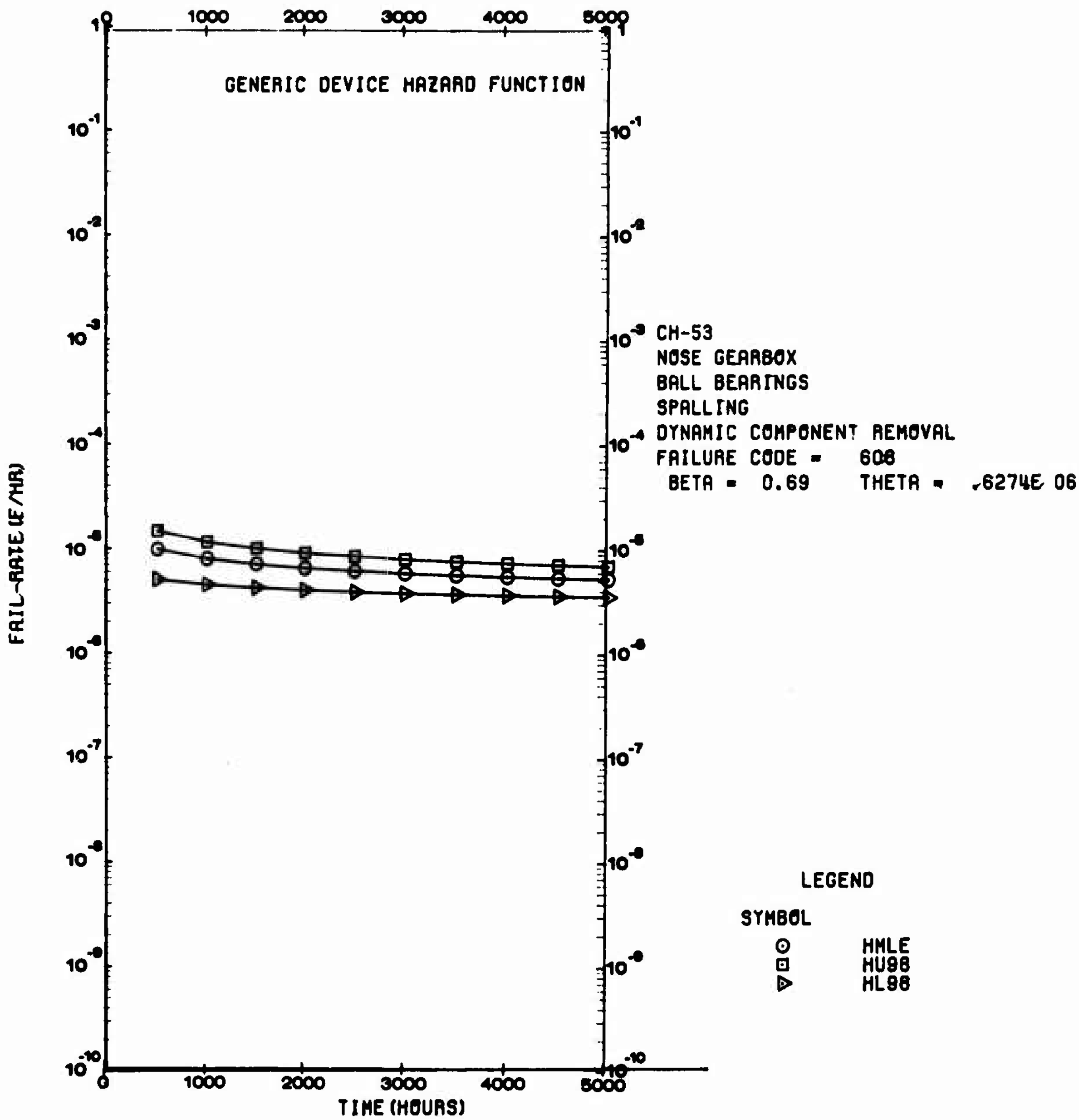

Figure 17. Bearing Spalling (Infant Mortality Failures) Hazard Function.

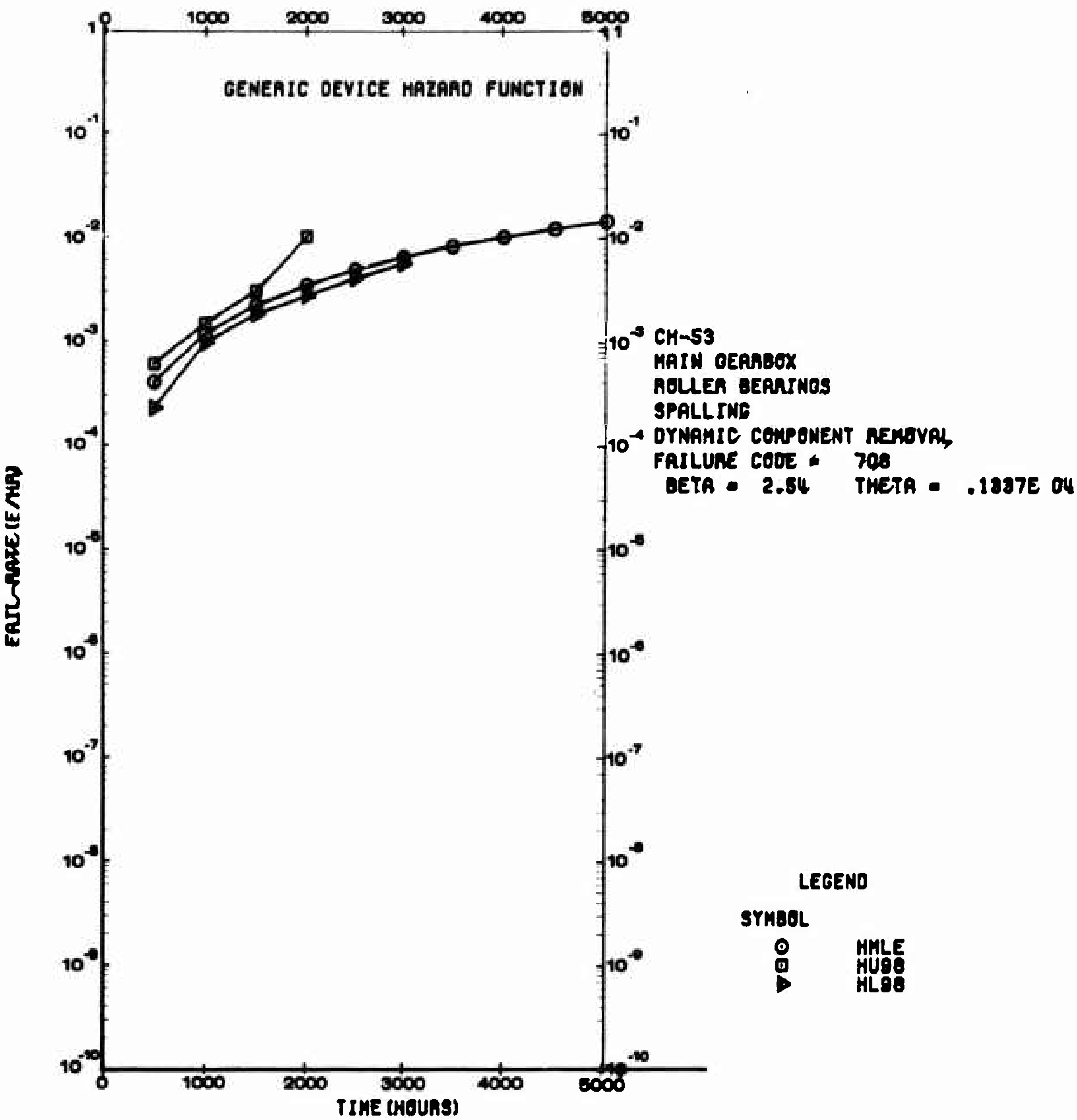

Figure 18. Bearing Spalling (Minimal Lubrication Impact) Hazard Function.

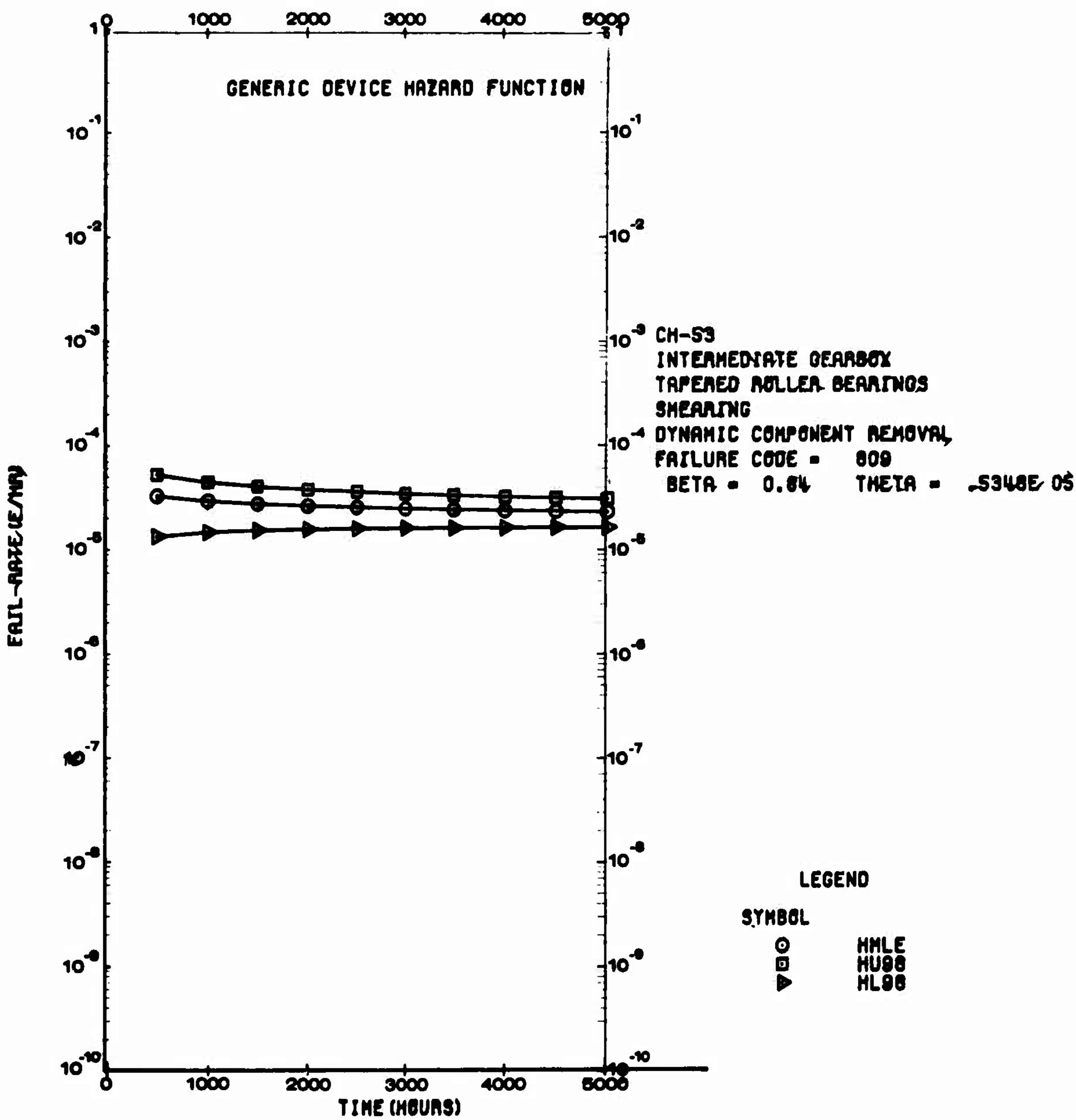

Figure 19. Bearing Smearing Hazard Function.

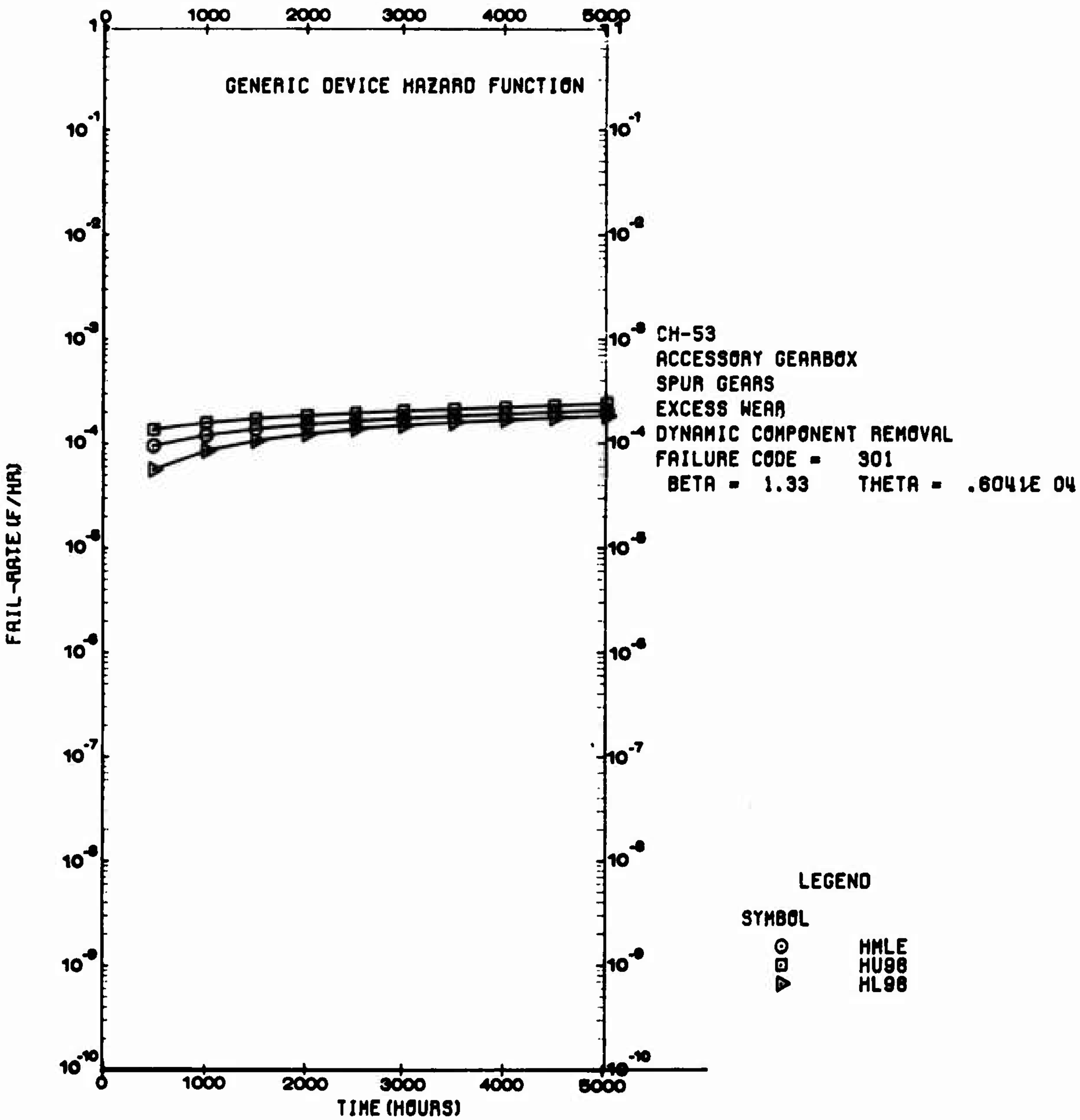

Figure 20. Spur Gear Excess Wear Hazard Function.

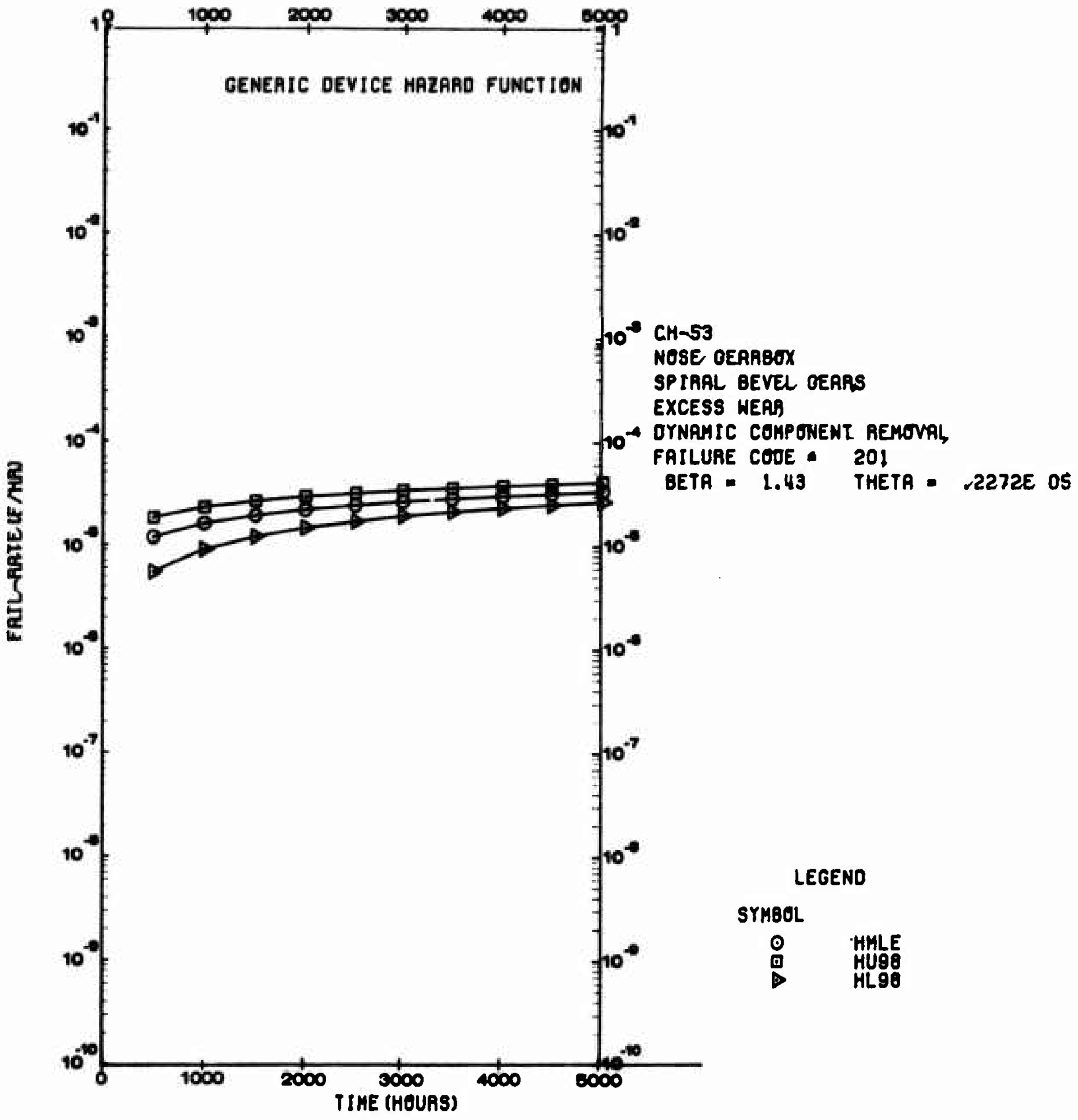

Figure 21. Spiral Bevel Gear Excess Wear Hazard Function.

not possible to determine which mechanisms might be responsible. However, foreign particle abrasions and normal sliding that occurs when gear teeth mesh are likely candidates. The amount of surface wear from abrasion depends on the relative hardness of materials involved and the rate of buildup. The amount of material removed by sliding is a function of the normal loads, the sliding distance, and the surface hardness. Either of these mechanisms could result in comparable hazard function shapes. As a result, the significance of a common shape for the hazard functions is not known. Nevertheless, wear is seen to be a very high time failure mode by the values of "theta". Certainly these failure modes can be tolerated since they do not affect safety-of-flight.

Figure 22 is the only CH-53/54 spiral bevel gear or spur gear hazard function for tooth fracture or pitting that is increasing. All Sikorsky gears are designed for infinite life by AGMA methods.[5, 6, 7, 8, 9, 10] Figure 23, which is typical of tooth fracture hazard functions, seems to confirm this result. The fact that "theta" is greater than 10,000 hours, which is equivalent to about 10^{10} cycles, indicates that damage is not incurred every cycle since steel's S/N curve is generally flat after 10^7 cycles.[11] As a result, it is suspected that damage cycles are the result of transient loads that may exist on the gear shaft from time to time. This case shows why it is important to know the dynamic response of the drive train and the stress distribution of gear tooth loads. No life limit is needed because safety of flight is not affected, nor does the hazard function significantly affect the nose gearbox hazard function.

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5 "Design Procedure for Aircraft Engine and Power Take-Off Bevel Gears", AGMA Standard 431.02, March 1964.

6 "Design Procedure for Aircraft Engine and Power Take-Off Spur and Helical Gears", AGMA Standard 411.02, September 1966.

7 "Surface Durability (Pitting) of Spur Gear Teeth", AGMA Standard 210.02, January 1965.

8 "Surface Durability (Pitting) Formulas for Spiral Bevel Gear Teeth", AGMA Standard 216.01, January 1964.

9 "Rating Strength of Spur Gear Teeth", AGMA Standard 220.02, August 1966.

10 "Rating the Strength of Spiral Bevel Gear Teeth", AGMA Standard 223.01, January 1964.

11 AGMA Standard 411.02's life factors infer that the S/N curve has the same shape slope after 10^7 cycles as it does before 10^7 cycles for spur gears. However, AGMA Standard 431.02 indicates the S/N curve is flat after 10^7 cycles for spiral bevel gears. Why one curve has a knee and the other does not is not clear.

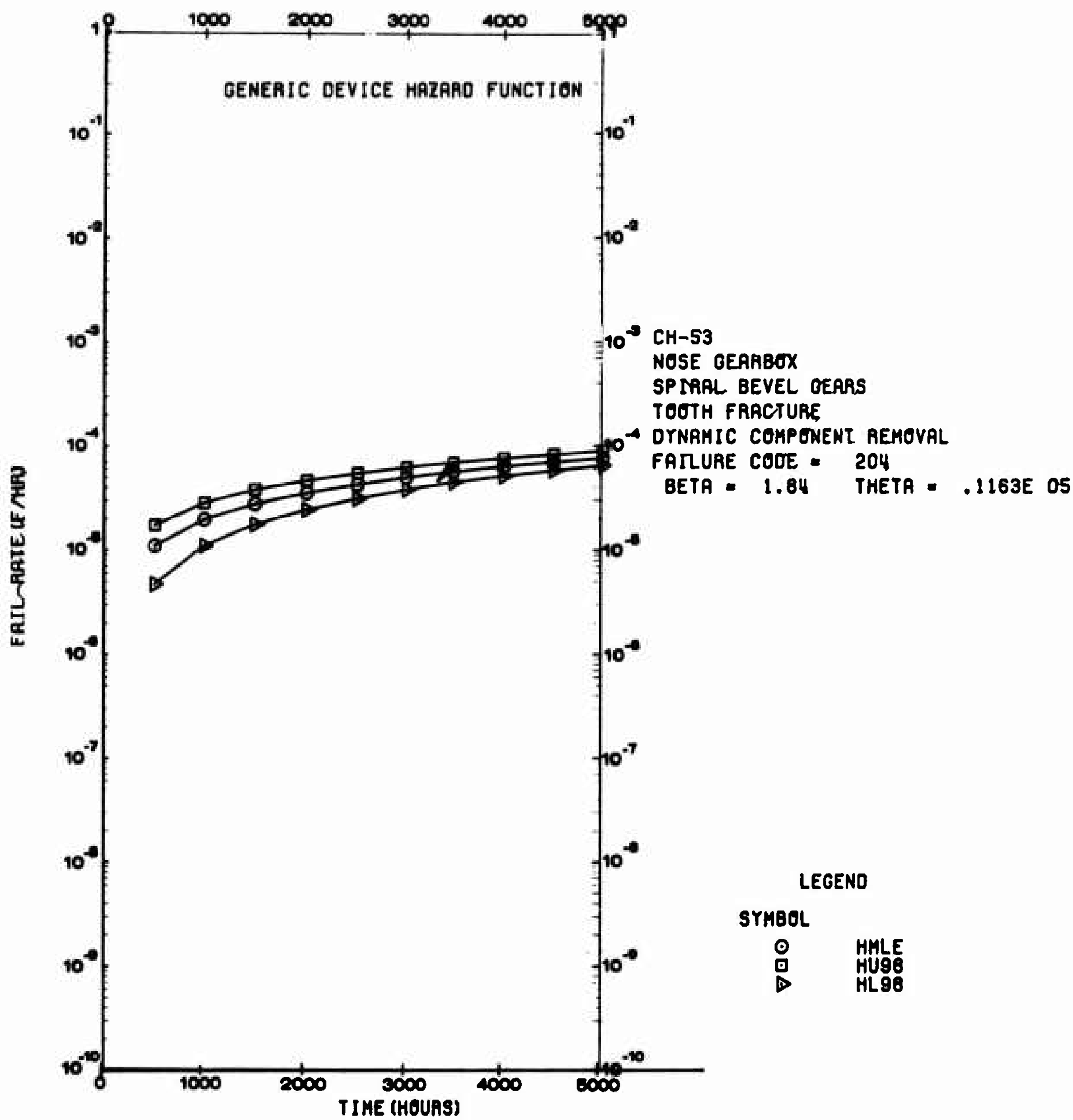

Figure 22. Spiral Bevel Gear Tooth Fracture Hazard Function.

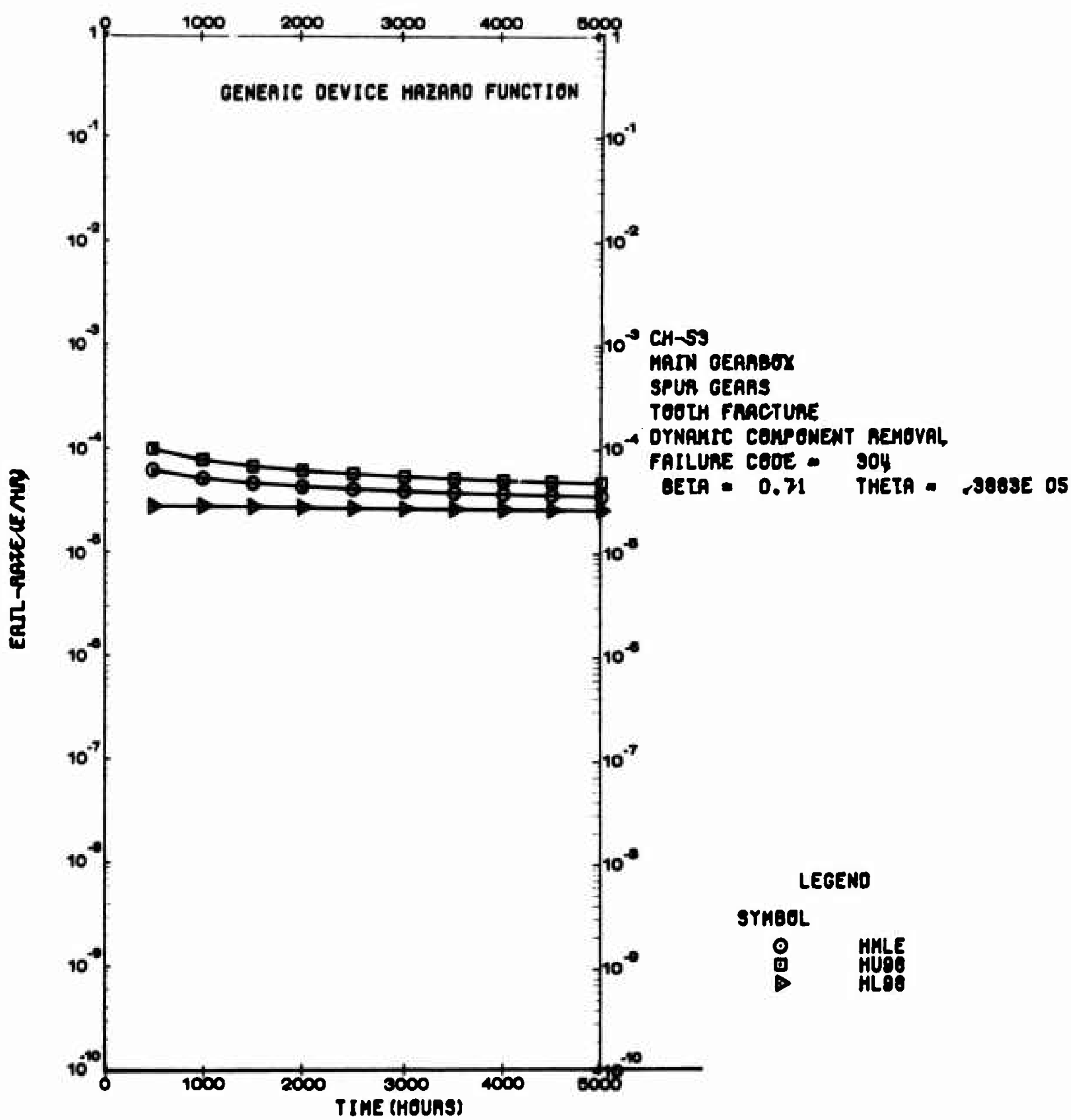

Figure 23. Typical Gear Tooth Fracture Hazard Function.

2.3.3 SPLINES

All spline failures that have been recorded in this study's data bank were of grease lubricated splines. Most of the problems result from the grease not being retained. When grease is lost, fretting causes the spline to wear rapidly. Eventually spline teeth will shear. Figure 24 shows the impact of this failure mechanism on the hazard function of CH-53 accessory gearbox spline couplings.

All spline couplings that have potential safety-of-flight failures are firmly held together with retention nuts so that relative motion is minimized. Furthermore, these shafts rotate at low rpm's so that the effect of grease moving away from mating surfaces due to centrifugal force is minimized. As a result, it is not surprising to find that no failures of these splines have occurred in over 660,000 flight hours of combined CH-53/54 experience.

Even though the failure modes of Figure 24 do not affect safety of flight, product improvement is desirable. Spline improvements will be discussed in Section 3 of this report.

2.3.4 NUTS

Locking assembly failures are usually expected to have a constant hazard function. Exceptions are when the shaft vibration causes the locking assembly to wear and the nut to subsequently back off, or when the shaft experiences a transient loading that causes the locking device to shear and the nut to subsequently back off. The hazard functions shown in Figures 25 and 26 are for locking assemblies which consist of a nut and a serrated washer with tangs that fit into slots on the nut. Serrations on the shaft and washer restrict the nut from backing off. Tangs insure synchronization of nut and lock washer movement. Most of the failures that were observed were caused by wear of the shaft serrations. The others were caused by fracture of the lockwasher. While these hazard functions do not significantly affect either gearbox hazard function, improvements can be made (See Section 3).

2.3.5 HOUSINGS

Housing crack hazard functions have generally been found to be increasing. Most failures were observed in the mounting lugs or bolt holes where the loads are the most concentrated. The other failures were primarily caused by housing corrosion. The CH-53 tail rotor gearbox's hazard function, which is shown in Figure 27, is the most significant one for housing cracks. Generally, most gearbox mountings are sufficiently redundant to permit loss of one load path from a fracture so that safety of flight is not adversely affected. Nevertheless, product improvement is desirable for implementing on-condition maintenance.

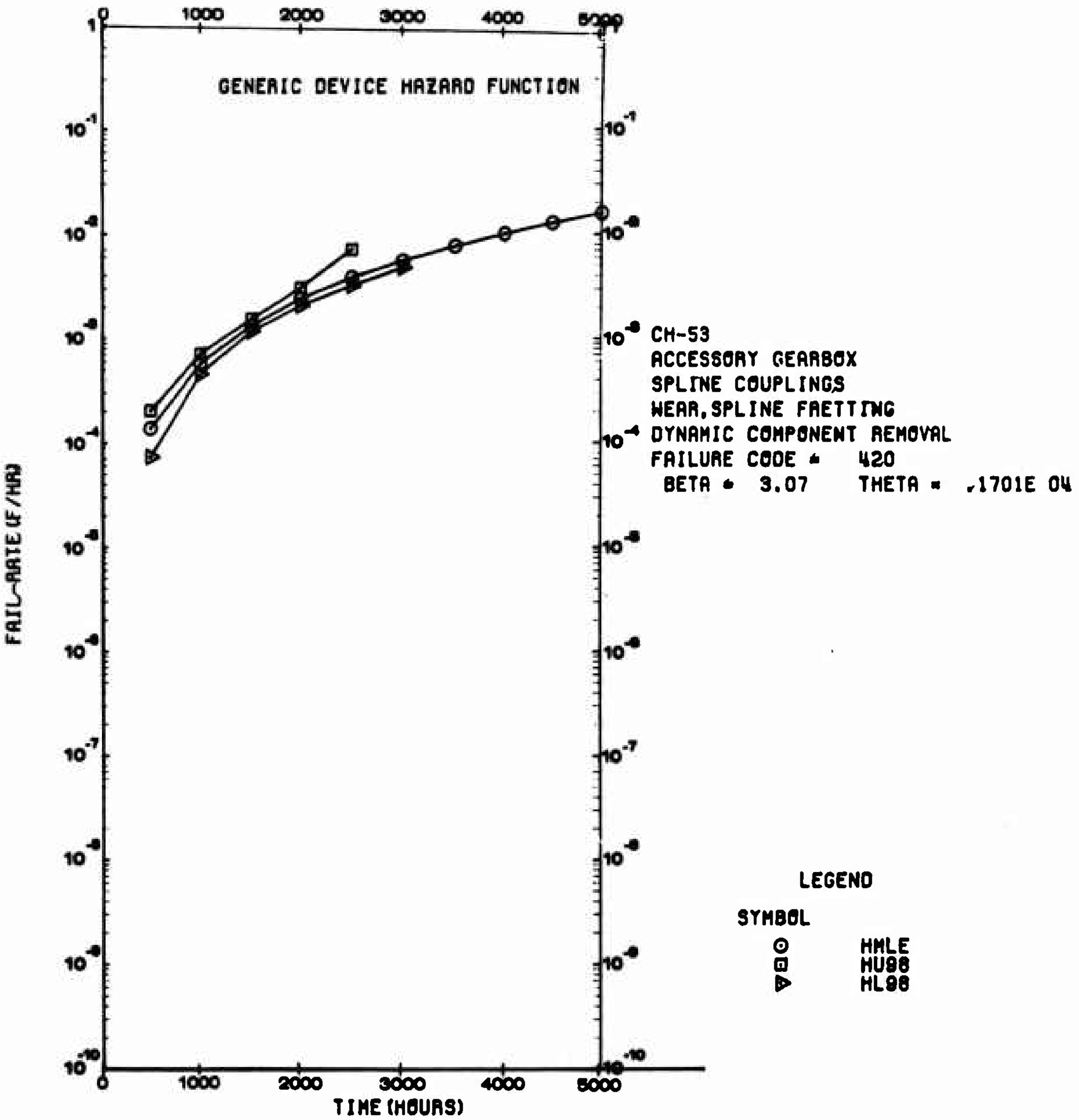

Figure 24. Spline Fretting Wear Hazard Function (Grease Retention Impact).

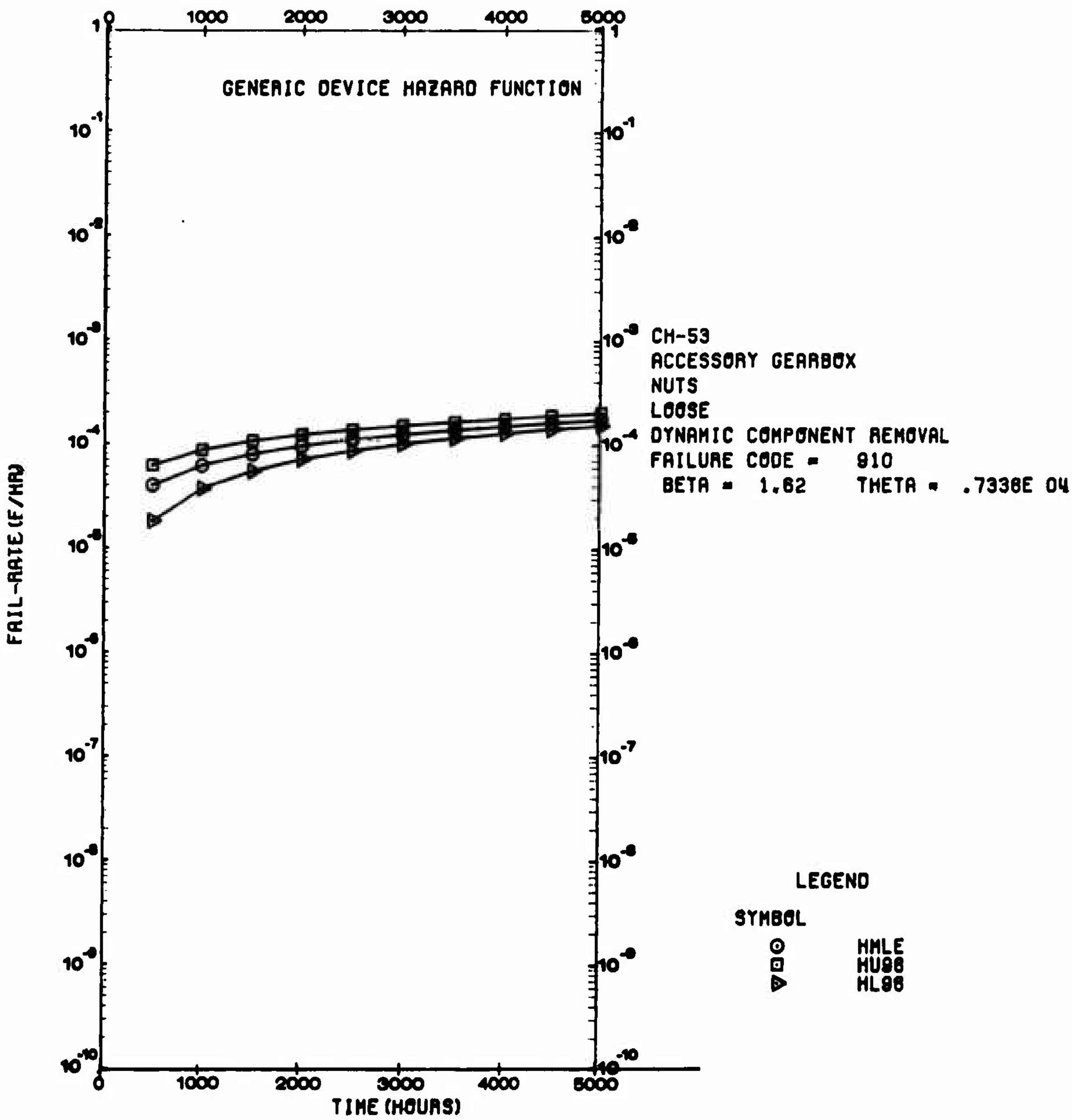

Figure 25. Locking Assembly Hazard Function (Shaft Vibration Impact - I).

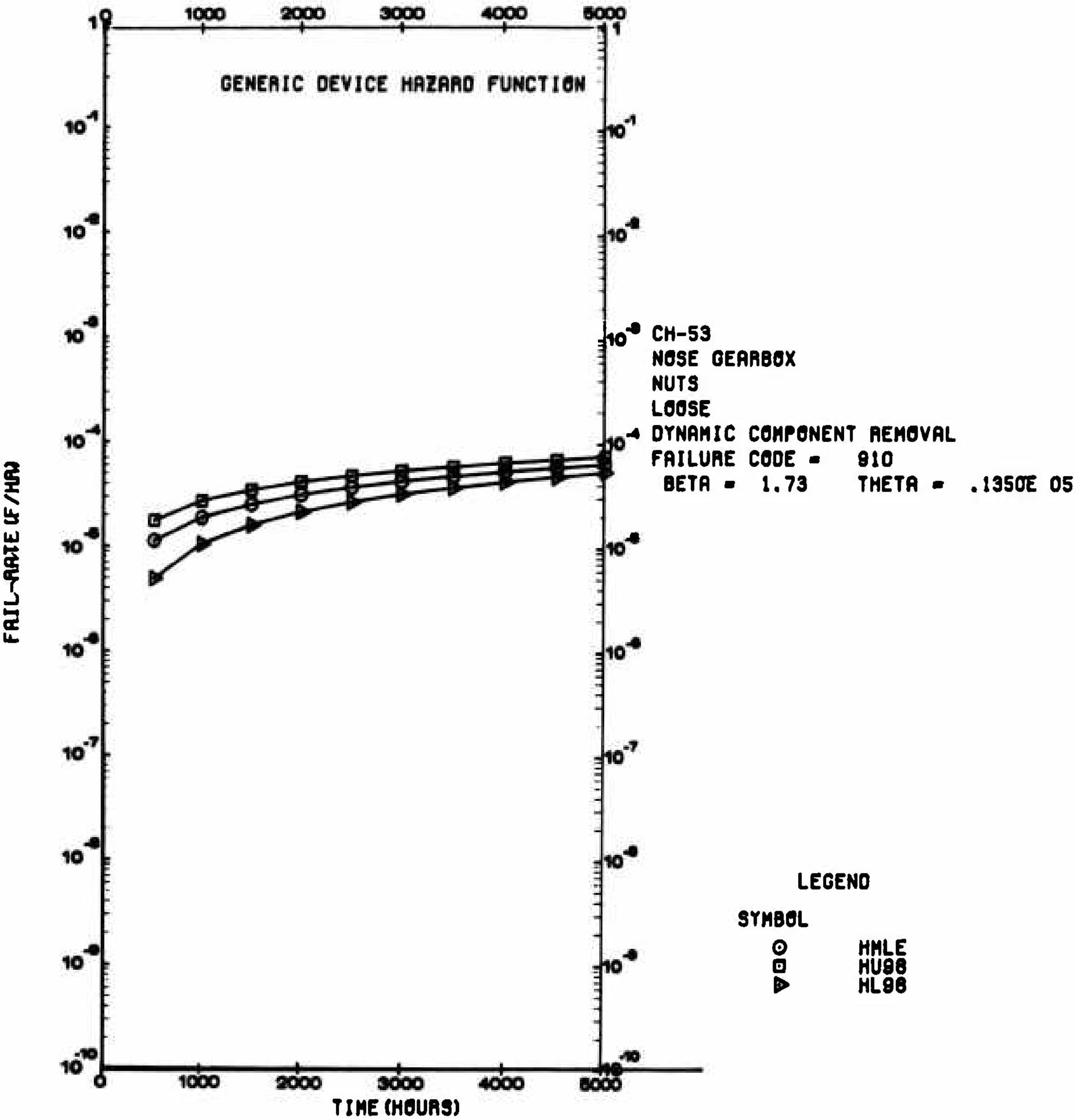

Figure 26. Locking Assembly Hazard Function
(Shaft Vibration Impact - II).

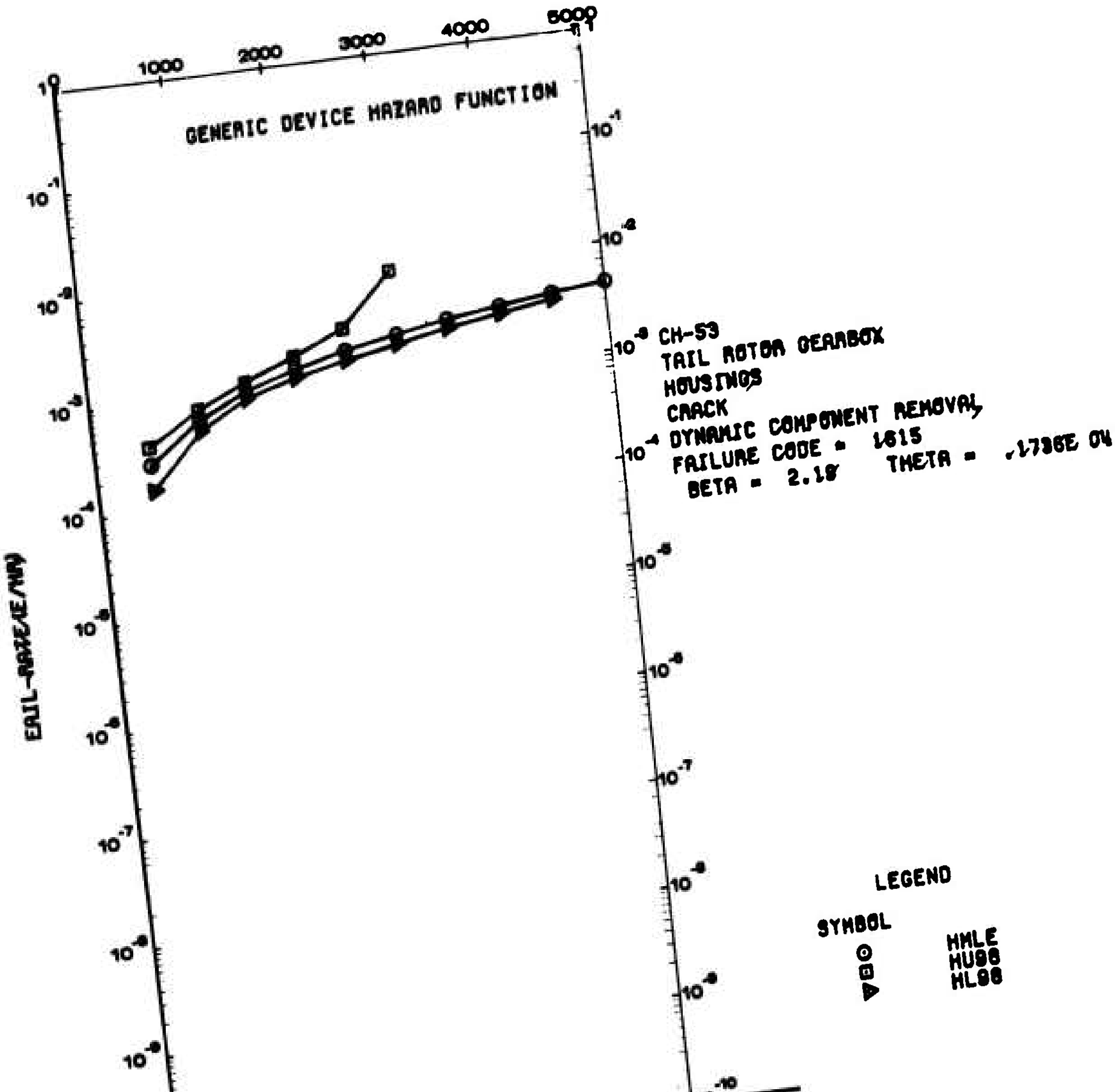

Figure 27. Gearbox Housing Hazard Function.

2.3.6 PUMPS

Pump hazard functions reflect infant mortality failures. The pumps used in the CH-53/54 gearboxes are four-bladed vane axial positive-displacement pumps. They are usually driven by a quill shaft. This type of pump has virtually no wearout failure modes that cause loss of oil pressure. The only parts that might exhibit wearout failure modes are internal support bearings and a positioning spring. However, due to the light loading of internal support bearings, there are no significantly increasing hazard functions. As a result, it is not surprising to see the pump hazard function shown in Figure 28 reflecting infant mortality failure modes.

2.3.7 FREEWHEEL UNITS

Conventional freewheel units (FWU's) possess failure modes similar to those of bearings, even though their operation is quite different. Their hazard functions generally reflect damage incurred during the time when they are overrunning, even though the actual failure may occur during direct coupling operation. Lubrication must be supplied adequately during overrunning and direct coupling operation. Figure 29 shows the impact of gravity oil feed to the lower members during the time when the FWU is overrunning. Clearly, product improvement is desirable to reduce the impact of this failure mode on the CH-54 main gearbox's dynamic component hazard function. FWU improvements are discussed in Section 3 of this report.

When adequate lubrication is supplied to FWU rollers during all phases of operation, their hazard functions are similar to those of bearings. A comparison of Figure 30 and Figure 16 illustrates this point.

2.3.8 SEALS

Most seal failure observed on the CH-53/54 are repaired by seal replacement rather than gearbox removal. The hazard functions shown in Figures 31 through 33 are only for those seal failures that resulted in gearbox removal. These failures include those where seal replacement could not stop excessive leakage due to impressions left on the shaft by the oil seal or those which failed in flight and caused secondary failures to the gearbox. Examples of the latter are failures that are caused by seal blowouts in flight or excessive external foreign particle contamination that severely damages the seal and internal gearbox components. A complete discussion of seal failure mechanisms, including those which can be repaired by seal replacement, is contained in the "Design Guide For Helicopter Transmission Seals".[12]

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[12] Hayden, T. S., and Keller, C. H. Jr., "Design Guide For Helicopter Transmission Seals", NASA Contractor Report CR 120997, NASA Lewis Research Center, National Aeronautics and Space Administration.

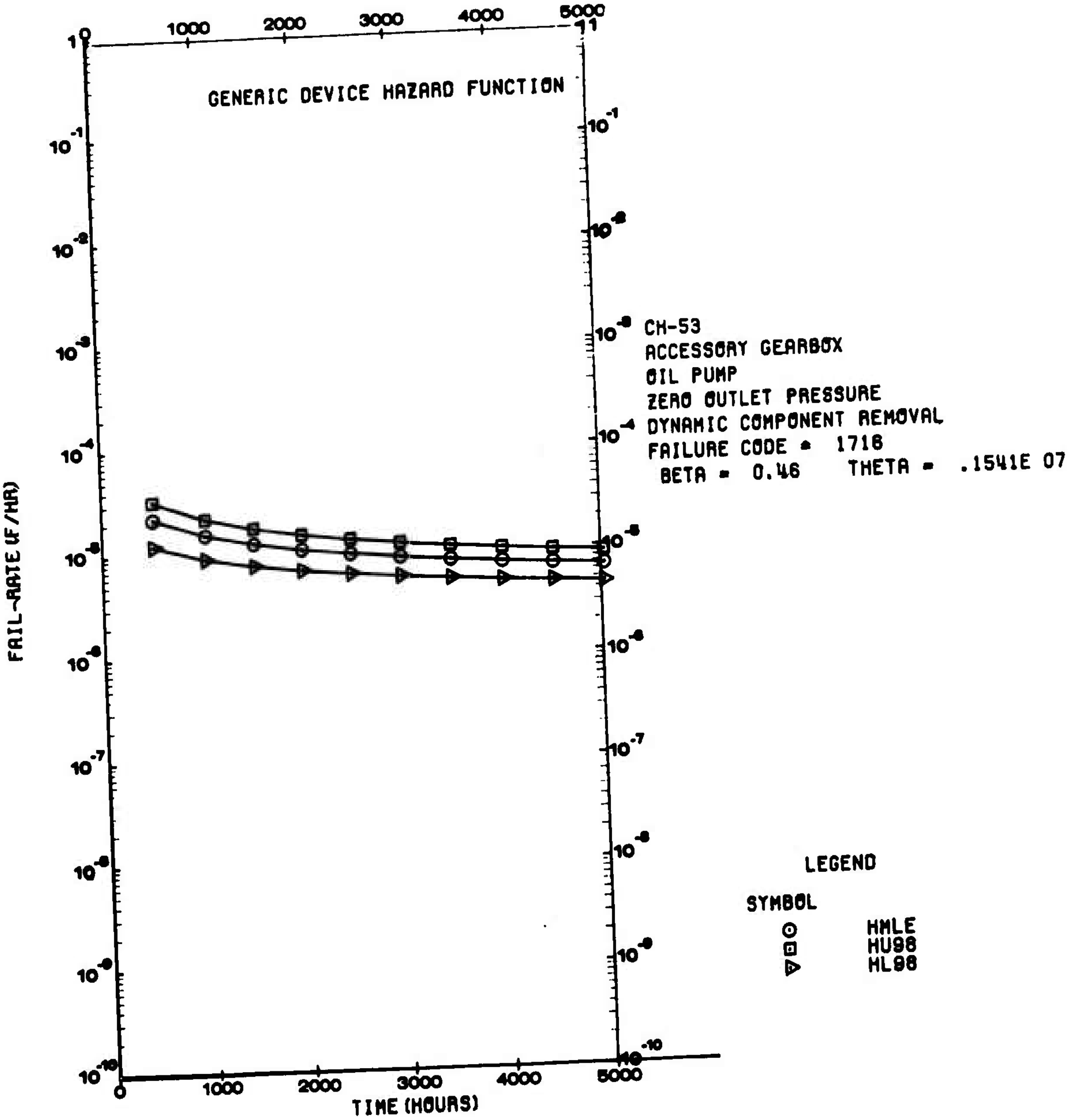

Figure 28. Oil Pump Hazard Function.

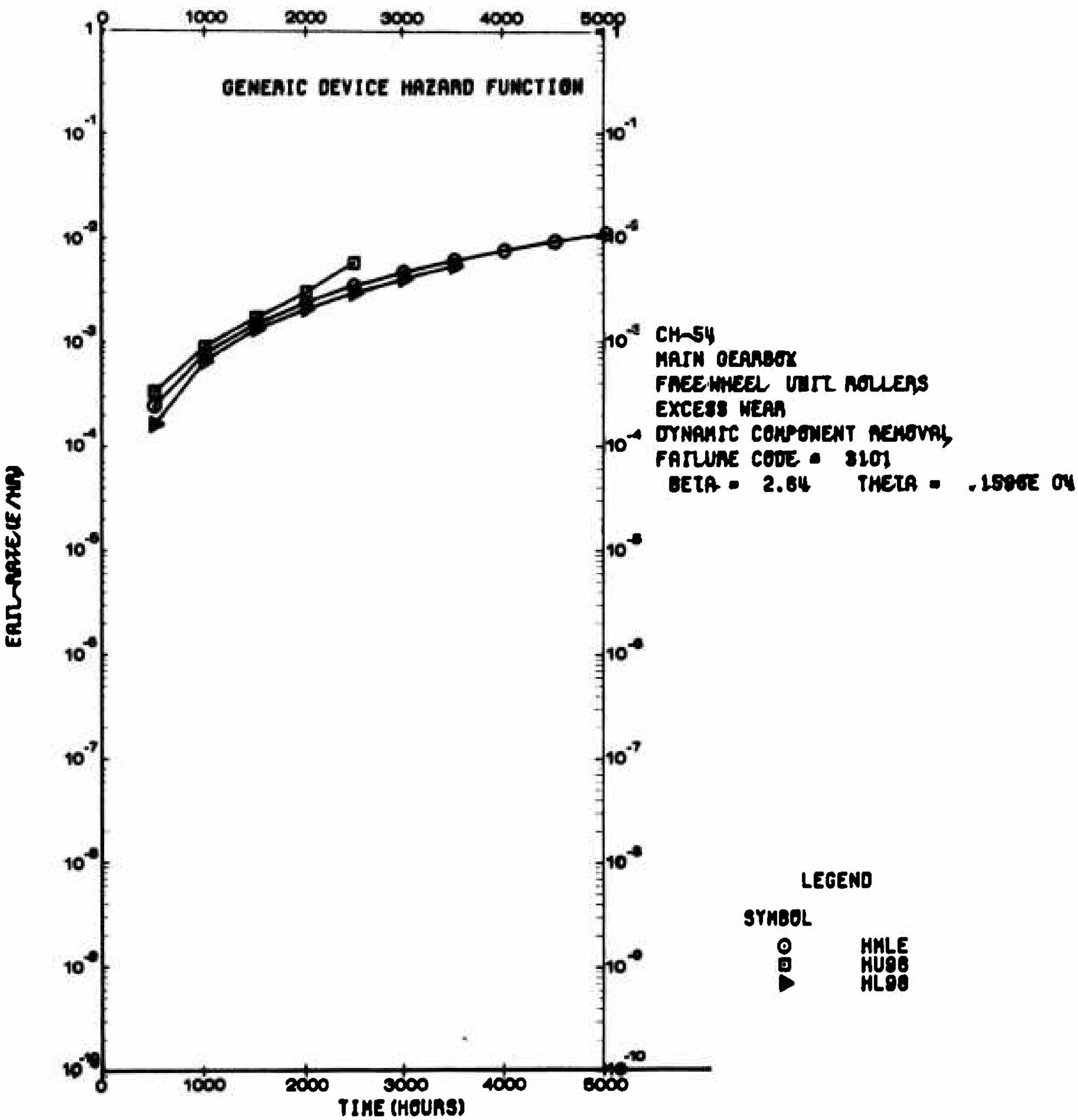

Figure 29. Freewheel Unit Roller Excess Wear Hazard Function (Minimal Lubrication Impact).

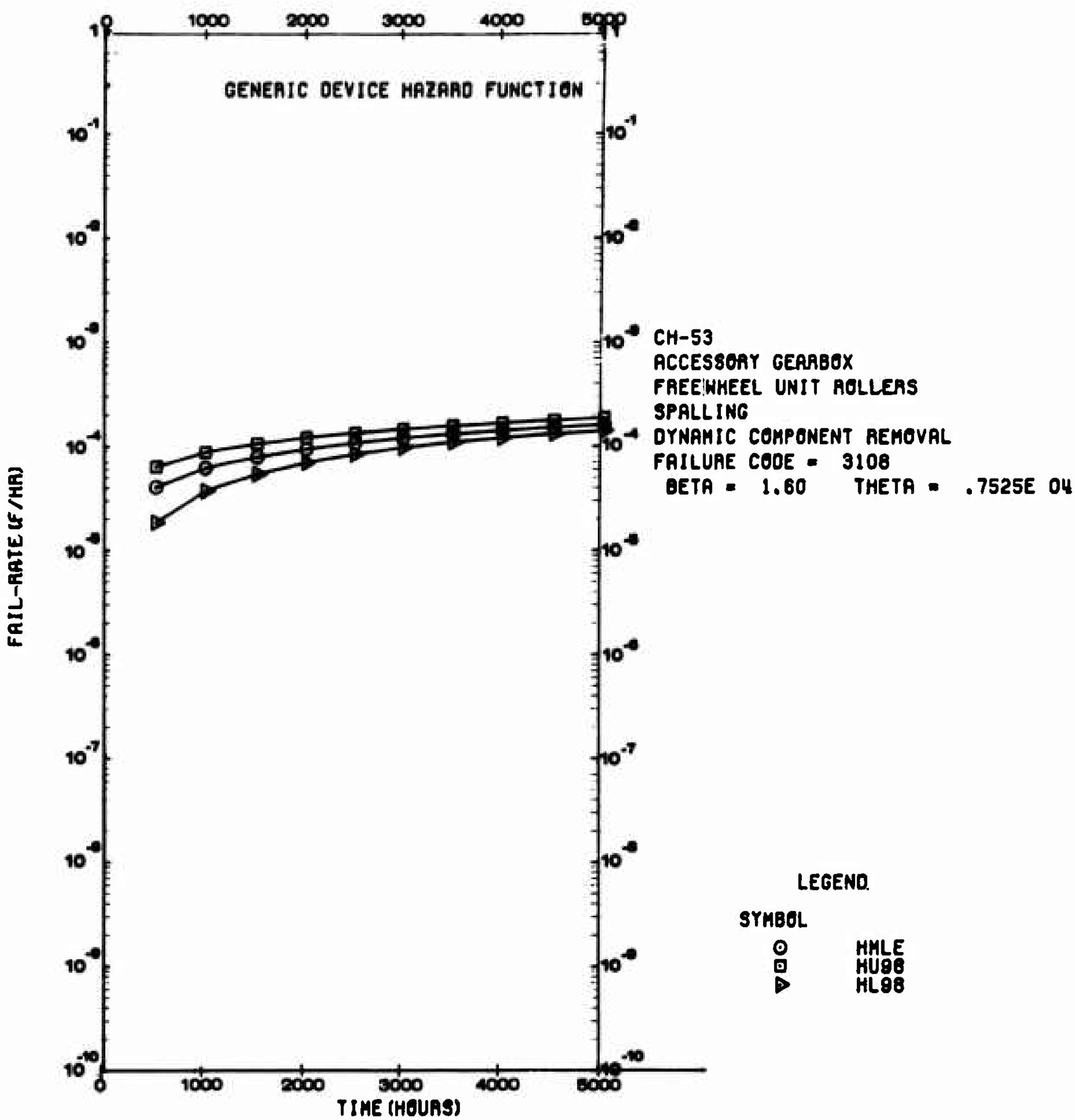

Figure 30. Typical Freewheel Unit Roller Spalling Hazard Function.

Two types of seals are employed in CH-53/54 gearboxes. Figures 31 and 32 primarily show the hazard functions of face seals used on high speed shafts. Figure 33 is a typical hazard function for lip seals. The fact that hazard functions in Figures 31 and 32 have significantly different shapes could be due to the distortion created by the effect of seals being replaced in lieu of a gearbox being removed when seal failures occur. No attempt was made to track operating times of individual seals that were replaced. Figures 31 through 33 only reflect high time failure modes. Failures caused by damage to the seal on installation or to the gearbox as a result of an improper installation generally result in a decreasing hazard function (infant mortality failure mode). While Figures 32 and 33 indicate that product improvements are desirable, none are foreseen that would radically alter the shape of the hazard function. Recommended seal design practices that enhance on-condition maintenance are contained in the "Design Guide For Helicopter Transmission Seals." [12]

2.3.9 CLIPS AND BEARING RETAINERS

Hazard function behavior for clips and bearing retainers is similar to that for locking assemblies discussed in Section 2.3.4. Figure 34 is a typical hazard function for retainers which fail from occasional transient loadings that appear on a shaft. However, Figure 35 shows the impact of wear on CH-53 main gearbox sun gear clips. These clips restrain axial movement of the sun gear with respect to the main bevel gear shaft (see Figure 9). Shaft vibration causes the end of the clip to wear from rubbing against the main bevel gear shaft. While sun gear clip failures do not affect safety-of-flight, and contribute, at most, only 13% to the main gearbox's removal rate, improvements can be made to reduce clip wear (see Section 3).

2.3.10 BUSHINGS AND PITCH CHANGE CONTROL ROD ANTIROTATION GROOVES

Bushings and the pitch change control rod antirotation groove are interfacial hardware between the drive and flight control systems of the CH-53/54 tail rotor gearbox. Those components have wear failure modes resulting from the relative linear motion between the pitch change control rod and the output drive shaft. Hazard function shapes of these two are not expected to be the same since different materials are involved. The antirotation groove involves steel rubbing against oil lubricated titanium, and the bushing involves titanium rubbing against oil lubricated bronze. Figures 36 and 37 are resultant hazard functions. The significant increase by the antirotation groove's hazard function indicates that improvement is desirable.

The failure modes of Figures 36 and 37 were detected by oil analysis (Spectrum Oil Analysis Procedure). As a result, they are as valid as the test and criteria allow. Differences in criteria for rejection can lead to differences in what is called a failure. This point is clearly illustrated by comparing Figures 37 and 38, which reflect the difference between Sikorsky and service procedures. Furthermore, they illustrate why good working thresholds must be established for a SOAP program.

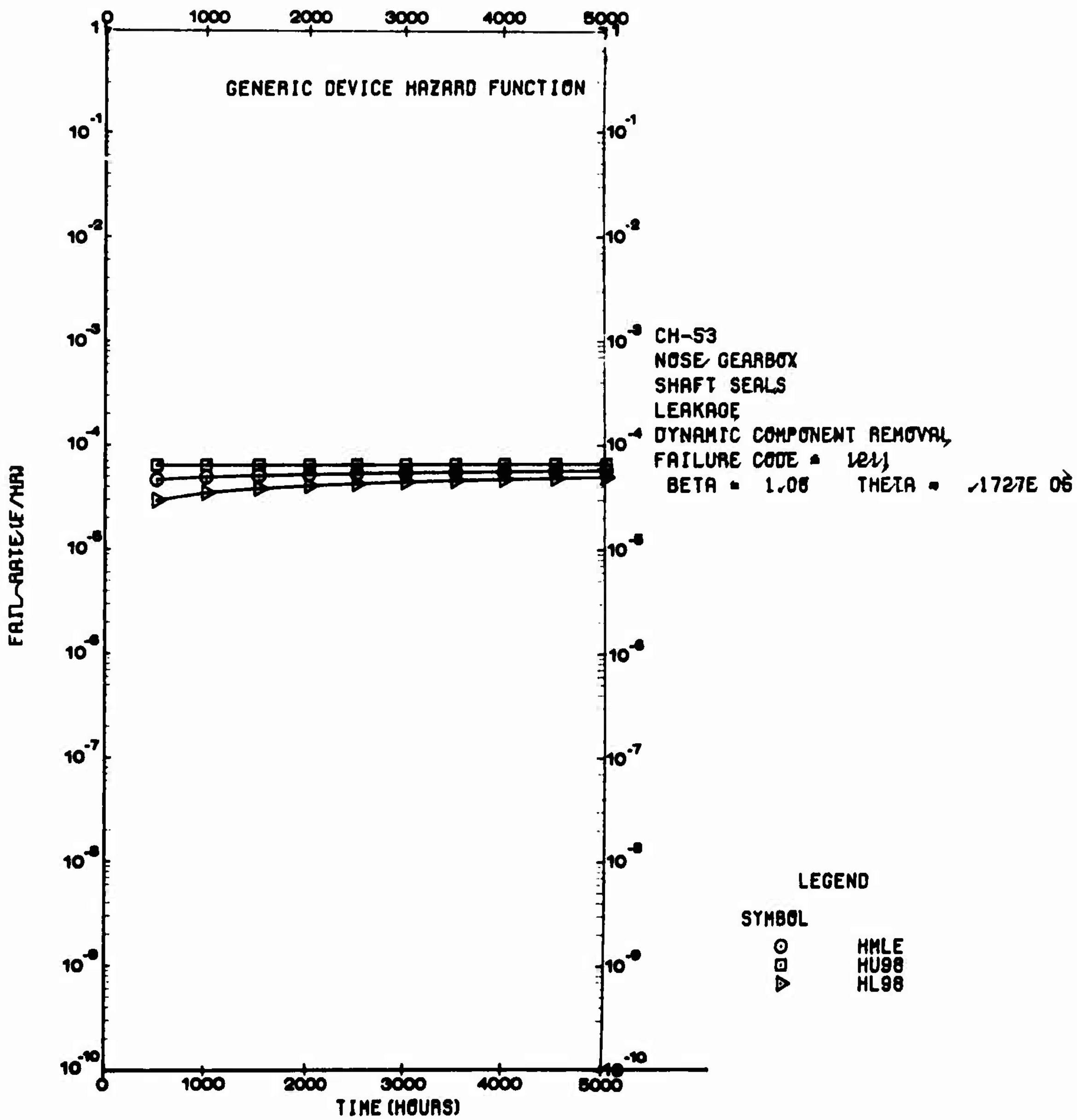

Figure 31. Face Seal Hazard Function.

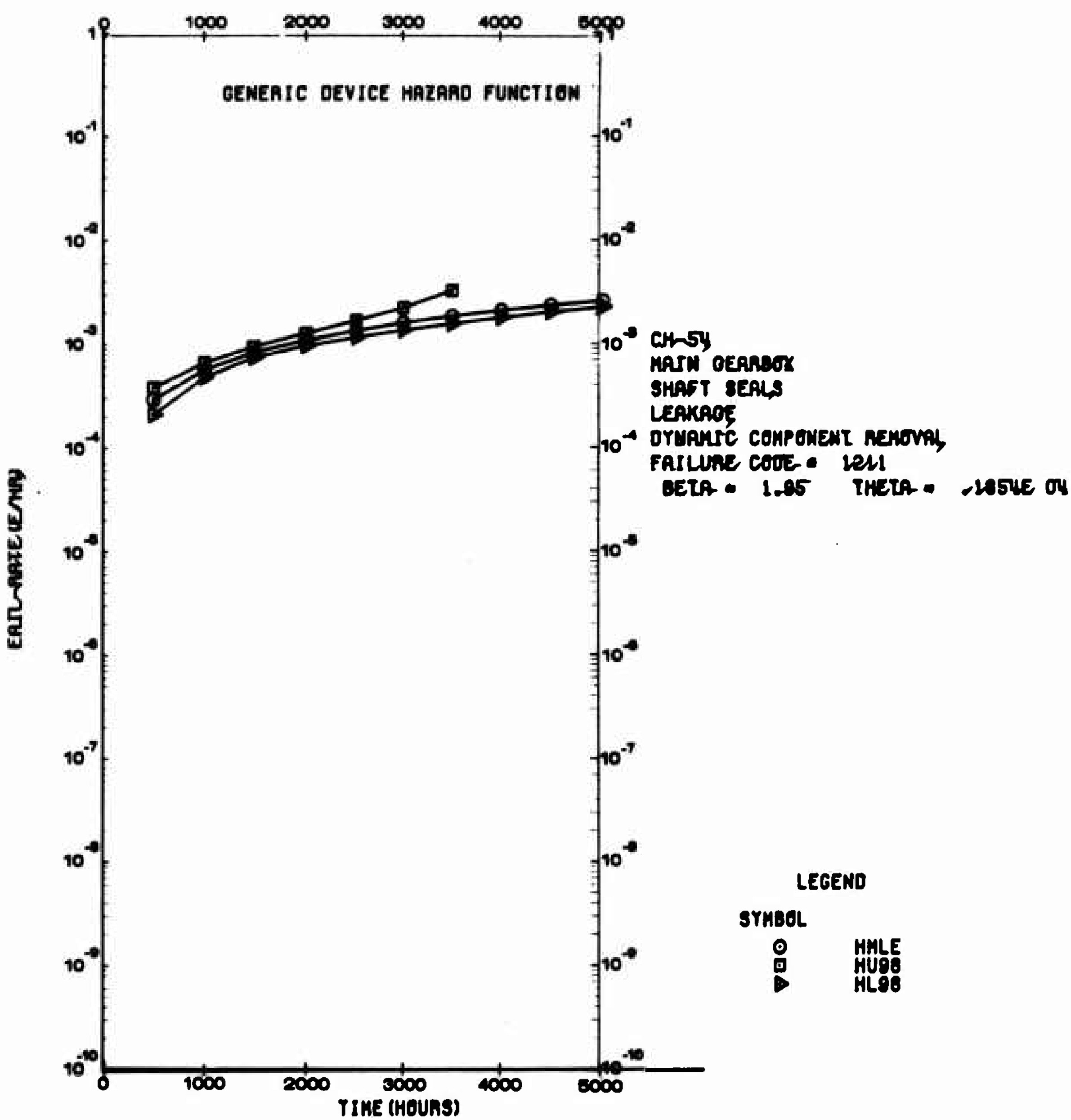

Figure 32. Shaft Seal Hazard Function.

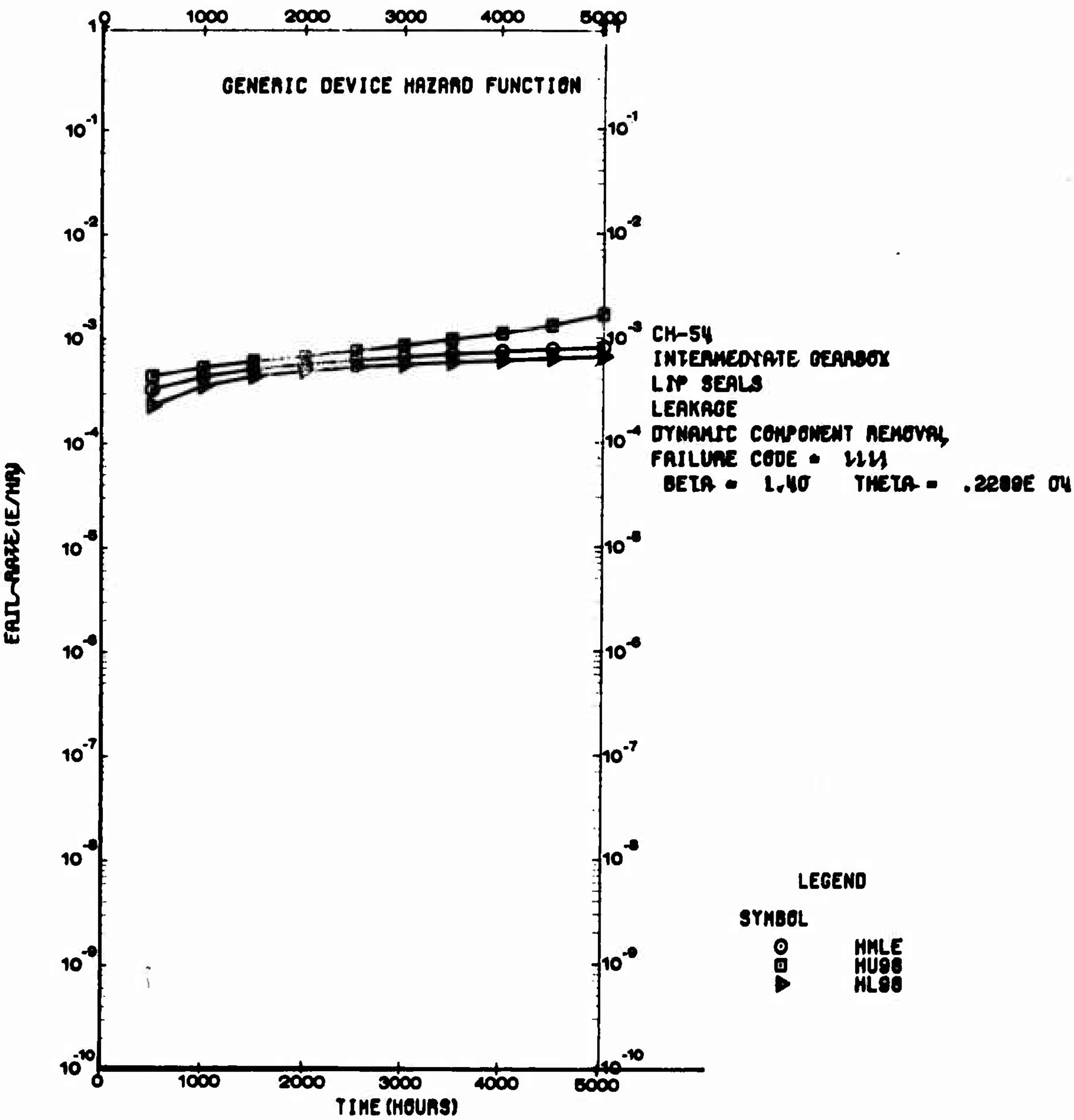

Figure 33. Lip Seal Hazard Function.

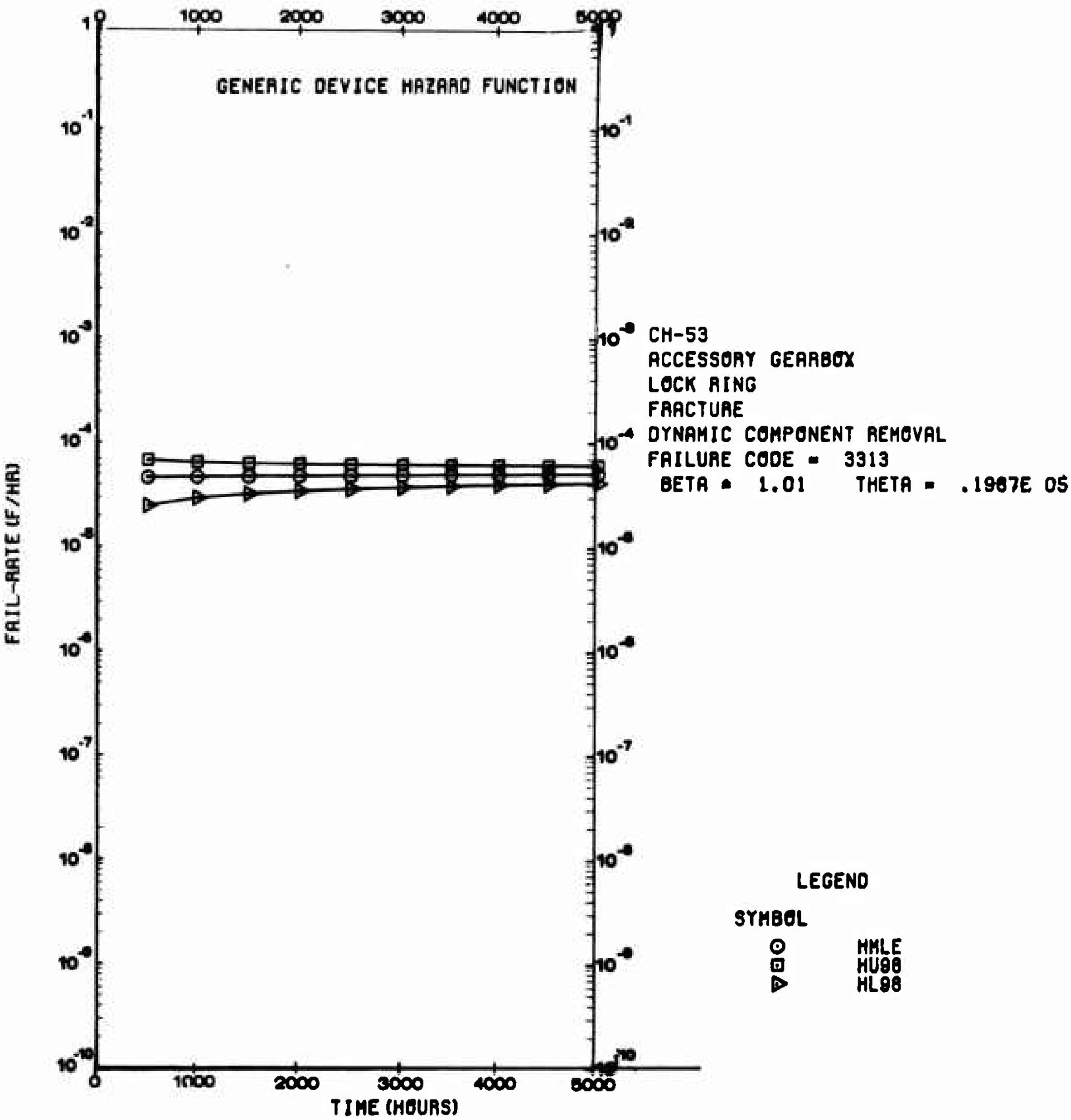

Figure 34. Lock Ring Hazard Function.

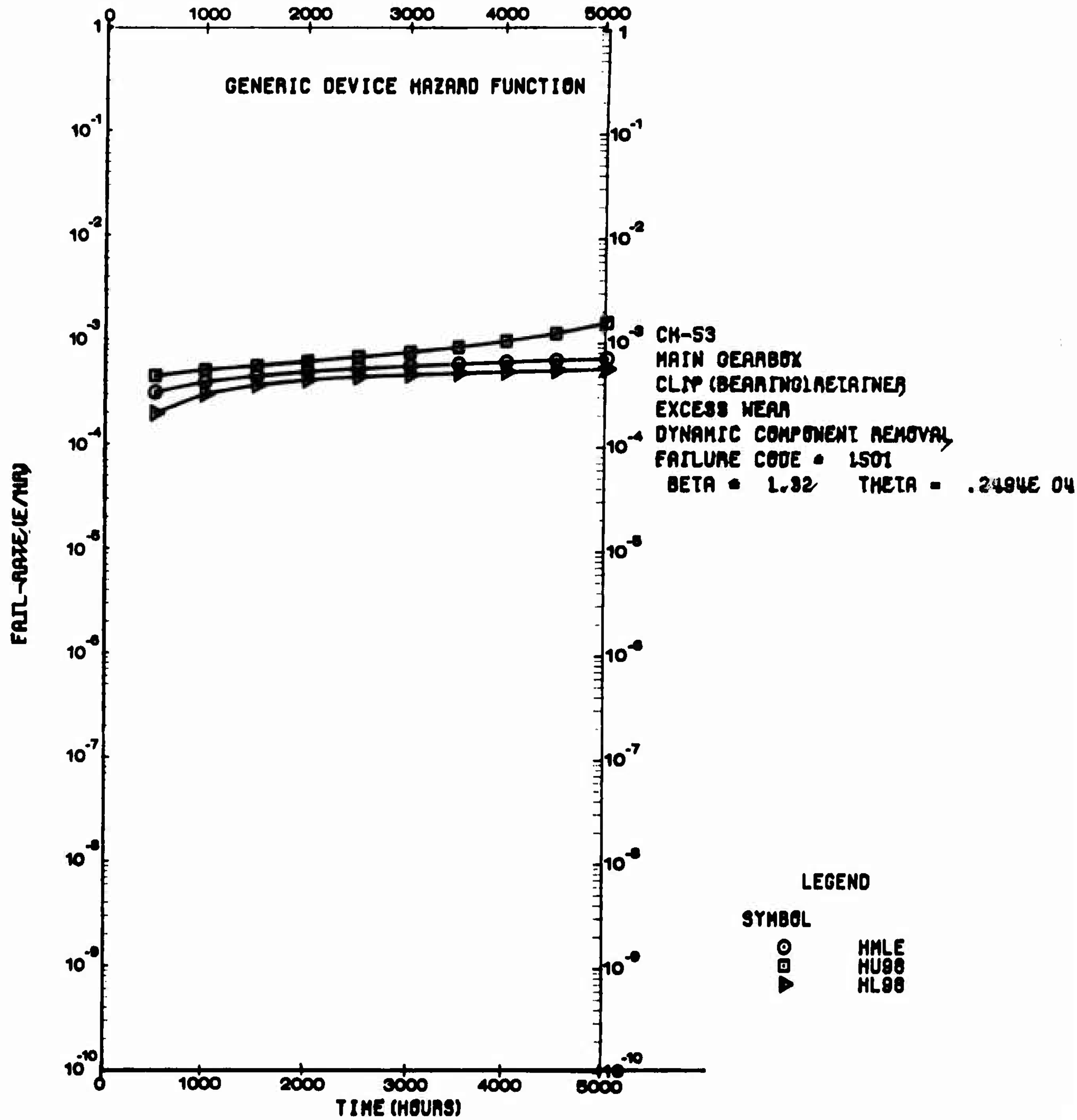

Figure 35. Clip Hazard Function.

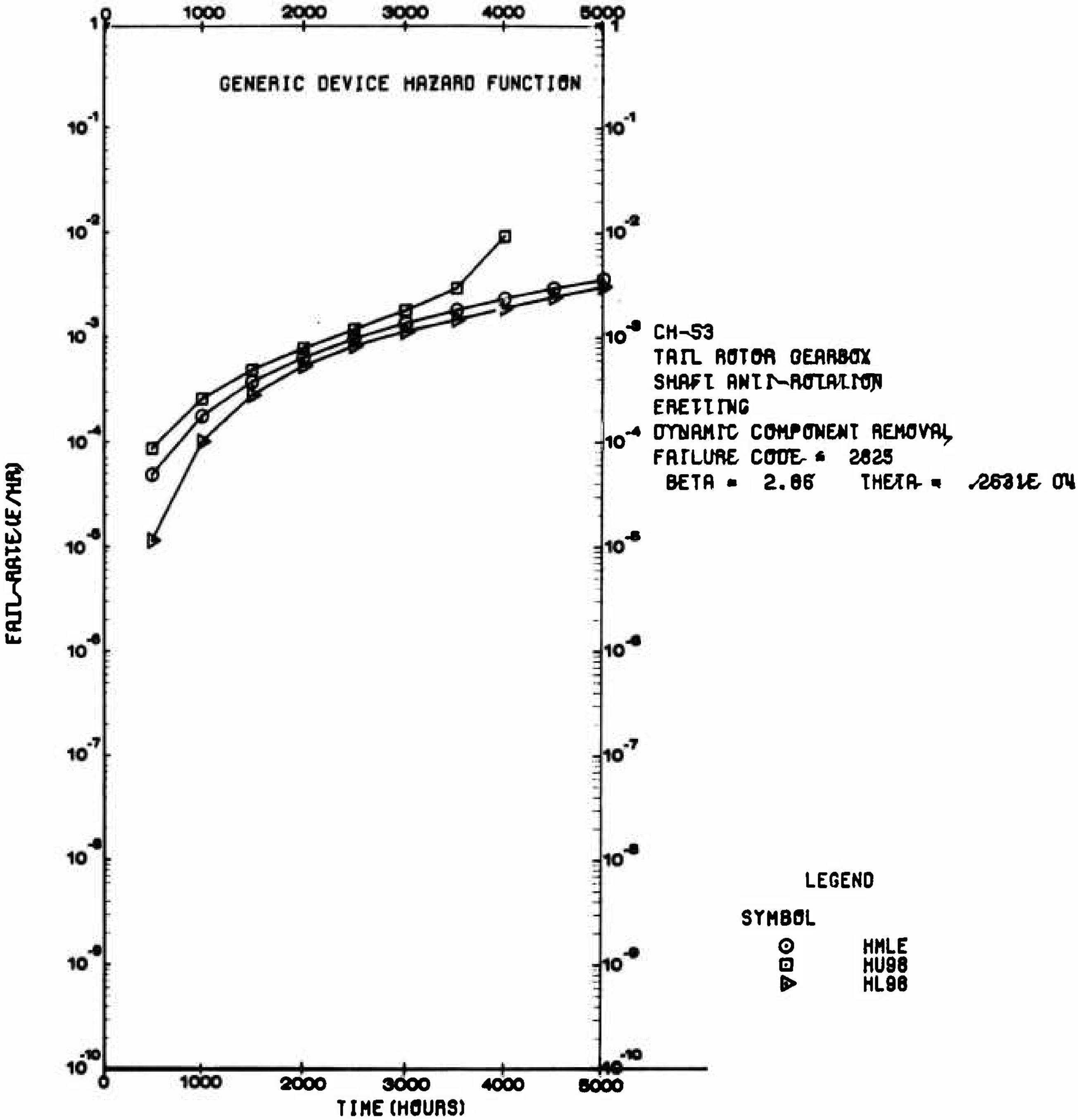

Figure 36. Pitch Change Shaft Antirotation Groove Fretting Hazard Function.

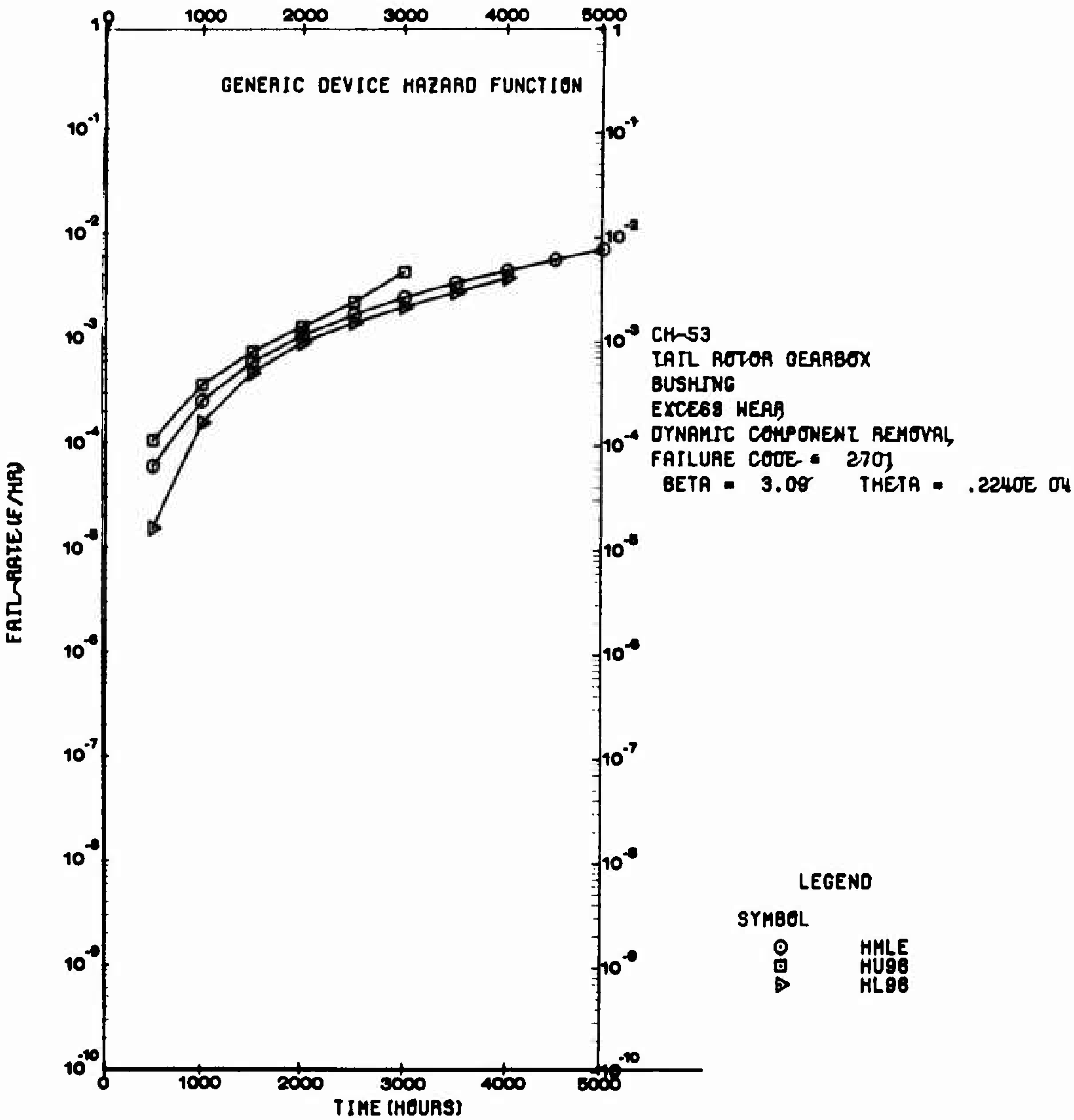

Figure 37. Bushing Excess Wear Hazard Function (SOAP Impact).

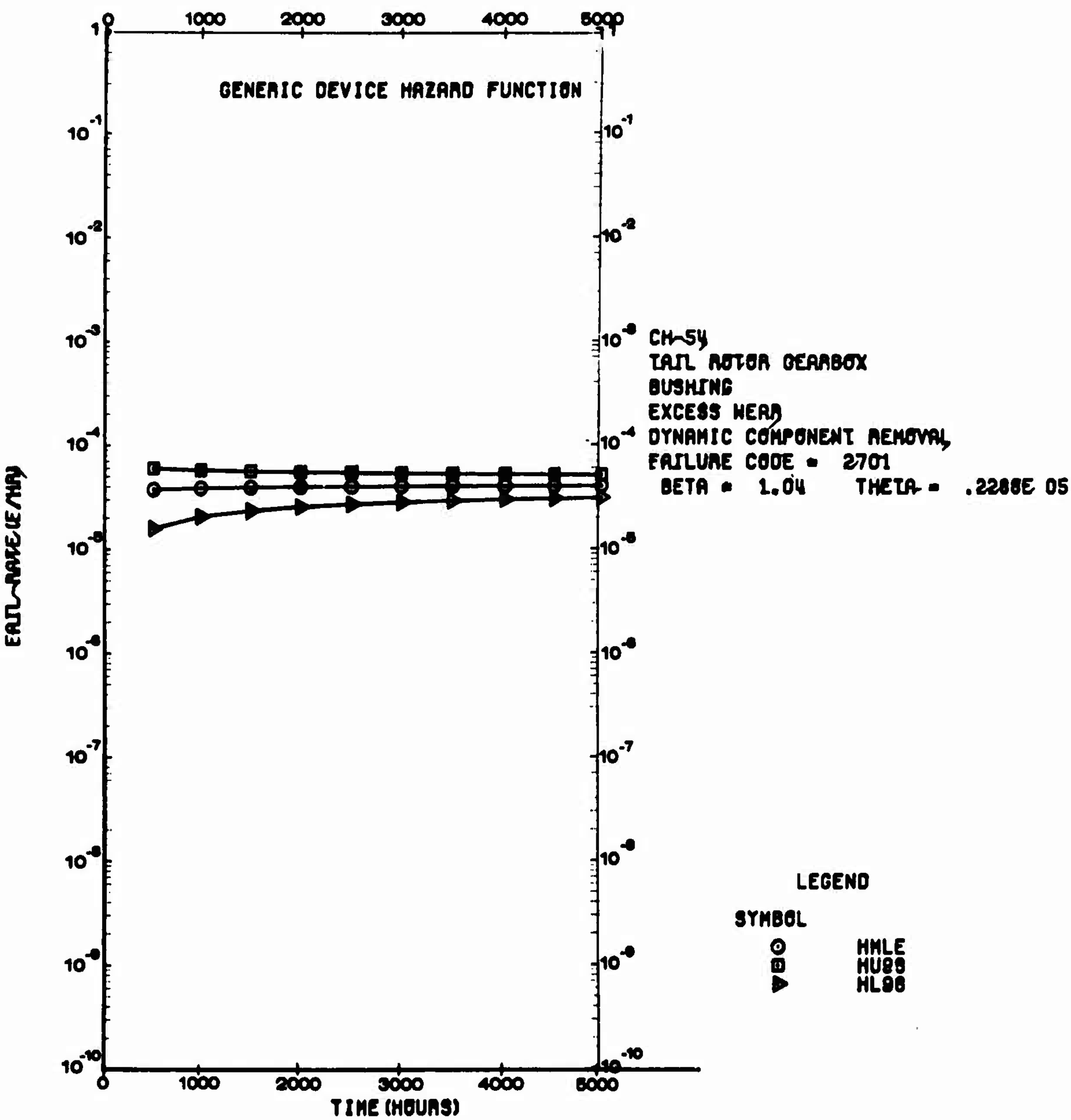

Figure 38. Bushing Excess Wear Hazard Function.

2.4 GEARBOX RELIABILITY

Before discussing hazard functions of CH-53/54 gearboxes, their reliability will be presented in more conventional terms. This is done not only to permit reliability to be expressed in more familiar terms, but also to allow comparison of CH-53/54 gearboxes with others. Table 15 summarizes each gearbox's reliability by its 99% confidence interval and observed value for the mean time between dynamic component removals for material failures. Both estimates reflect the time on failed components as well as the time on surviving ones. They assume that reliability is defined by the exponential distribution of the form $e^{-\frac{t}{\theta}}$.

The number of safety-of-flight malfunctions observed in CH-53/54 experience indicate the practicality of on-condition maintenance. In 445,000 flight hours, no safety of flight malfunctions were attributable to material failures of the H-53 drive train gearboxes. In 208,000 flight hours, only two safety-of-flight malfunctions occurred for which H-54 drive train malfunctions were a contributing factor. The fact that CH-53/54 experience includes aircraft that flew in Vietnam where situations required overtorque operation makes the above record more impressive.

2.4.1 GEARBOX HAZARD FUNCTIONS

Section 2.3 discussed how previous design practices impacted generic component hazard functions of CH-53/54 gearboxes. A feel for which failure modes are significant was developed. In this section, these results will be summarized to indicate where product improvement is necessary to implement an on-condition maintenance policy and where it is desirable to further enhance on-condition maintenance. Areas that are targeted for improvement will be those which have significantly increasing hazard functions. Failure modes with no experience data will be included to provide a complete accounting of failure modes that might occur if gearbox TBO's were extended from their values listed in Table 16 to 5000 hours. Hazard functions of failure modes with no experience data were estimated by methods described in Appendix A.

Very few failure modes have a significantly increasing hazard function. Figures 39 through 46 show the dynamic component removal hazard functions for CH-53/54 gearboxes. Table 17 shows the failure modes which significantly affect each hazard function at 5000 hours. This table shows that generally three failure modes account for more than 75% of the failure rate at 5000 hours. In all cases, there is one failure mode that is responsible for about 50% of the failure rate at 5000 hours. With the exception of the CH-53 nose gearbox, the significant contributors are failure modes with experience data. <u>This indicates that most failure modes which would affect a decision for on-condition maintenance are currently known</u>.

The CH-53 nose gearbox spur gear hazard function for excess wear was estimated from gearboxes that survived to the scheduled TBO which had parts removed at overhaul that indicated failure was possible before their next scheduled overhaul. Such failure modes, as discussed in Appendix A, are incipient failure modes. Admittedly, engineering judgement had to be used

TABLE 15. MEAN TIME BETWEEN DYNAMIC COMPONENT REMOVAL FAILURES SUMMARY

Aircraft	Gearbox	99% Confidence Interval (Hours)	Observed Mean (Hours)
CH-53	Main Gearbox	504 - 1444	820
	Nose Gearbox	2531 - 5494	3646
	Accessory Gearbox	947 - 2093	1376
	Intermediate Gearbox	1219 - 3297	1932
	Tail Rotor Gearbox	1215 - 3409	1957
CH-54	Main Gearbox	714 - 1513	1018
	Intermediate Gearbox	962 - 2700	1550
	Tail Rotor Gearbox	1942 - 11188	4156

TABLE 16. CURRENT CH-53/54 GEARBOX TBO's

Aircraft	Gearbox	TBO (Hours)
CH-54	Main Gearbox	800
	Intermediate Gearbox[a]	On-Condition
	Tail Rotor Gearbox	1200
CH-53	Main Gearbox	2000
	Intermediate Gearbox	2000
	Tail Rotor Gearbox	2000
	Nose Gearbox	2000
	Accessory Gearbox	2000

[a]When installed on CH-54A aircraft, the intermediate gearbox is operated on-condition. However, when installed on the CH-54B, the TBO is 1200 hours.

TABLE 17. SIGNIFICANT DYNAMIC COMPONENT REMOVAL FAILURE MODES

Aircraft	Gearbox	Generic Failure Mode	Percentage Contribution to Gearbox Hazard Function[a]
CH-54	Main	FWU Roller Excess Wear	60
		FWU Cage Fracture	10
		Shaft Seal Leakage	10
		Thrust Washer Excess Wear	5
	Intermediate	Lip Seal Leakage	46
		Housing Cracks	46
	Tail Rotor	Bushing Excess Wear	9
		Housing Cracks	35
		Antirotation Groove Wear	40
CH-53	Main	Roller Bearing Spalling	70
		Clip Excess Wear	5
		Ball Bearing Excess Wear	10
	Intermediate	Tapered Roller Bearing	50
		Spalling	25
	Tail Rotor	Housing Crack	30
		Antirotation Groove Wear	25
		Bushing	48
	Nose	Spur Gear Excess Wear	85
	Accessory	Spline Wear, Fretting	90

[a]At 5000 Hours.

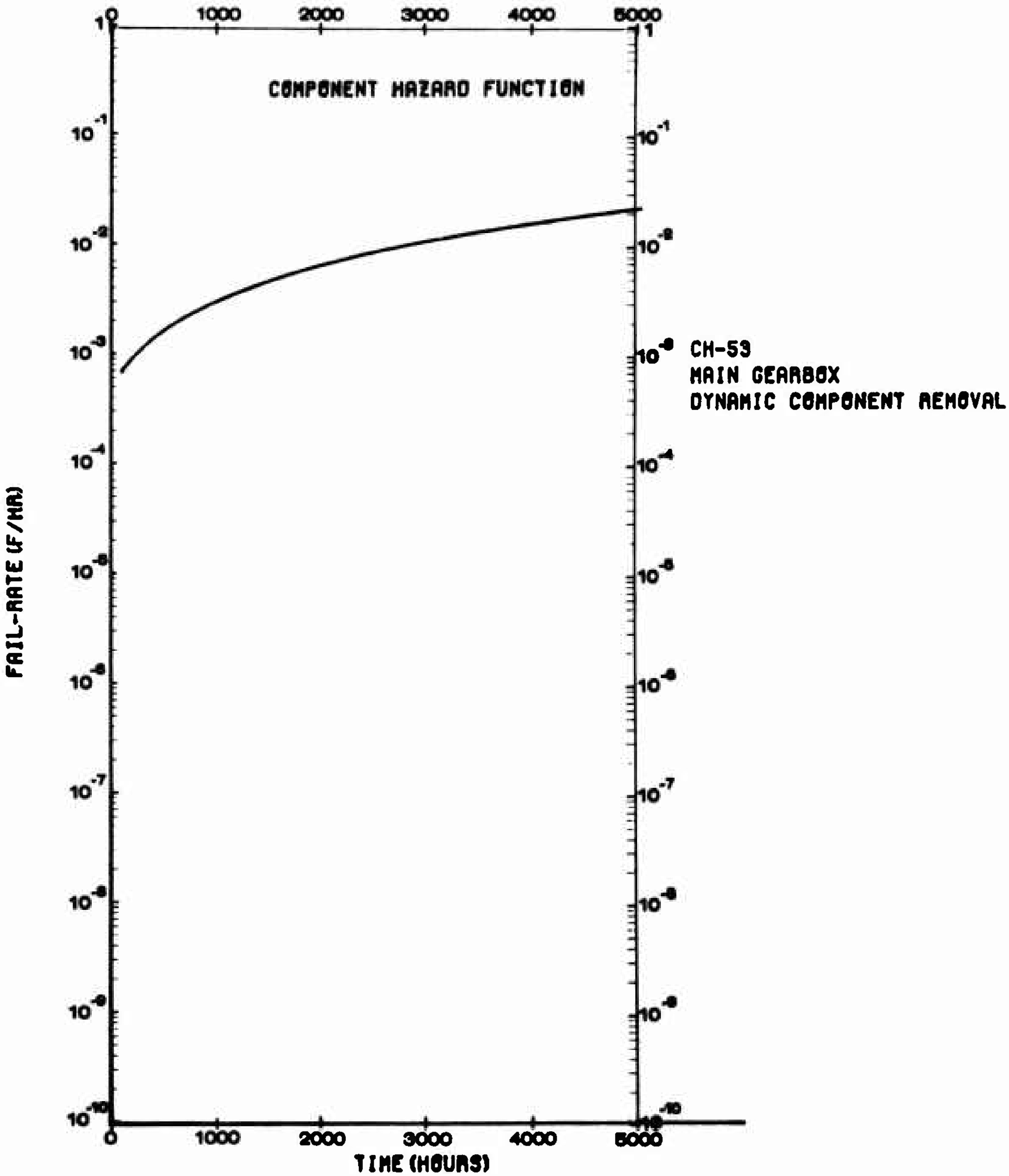

Figure 39. CH-53 Main Gearbox Dynamic Component Removal Hazard Function.

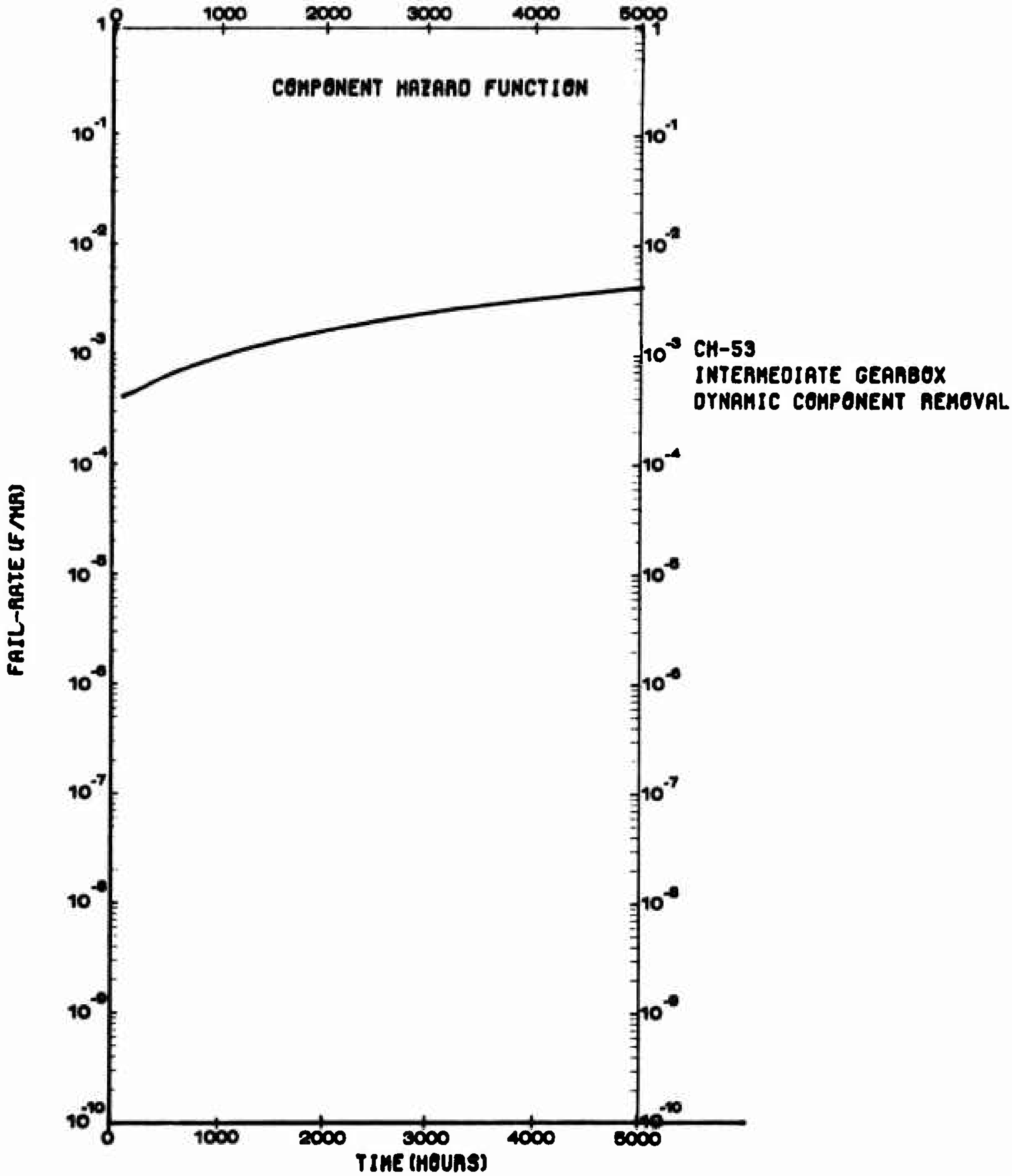

Figure 40. CH-53 Intermediate Gearbox Dynamic Component Removal Hazard Function.

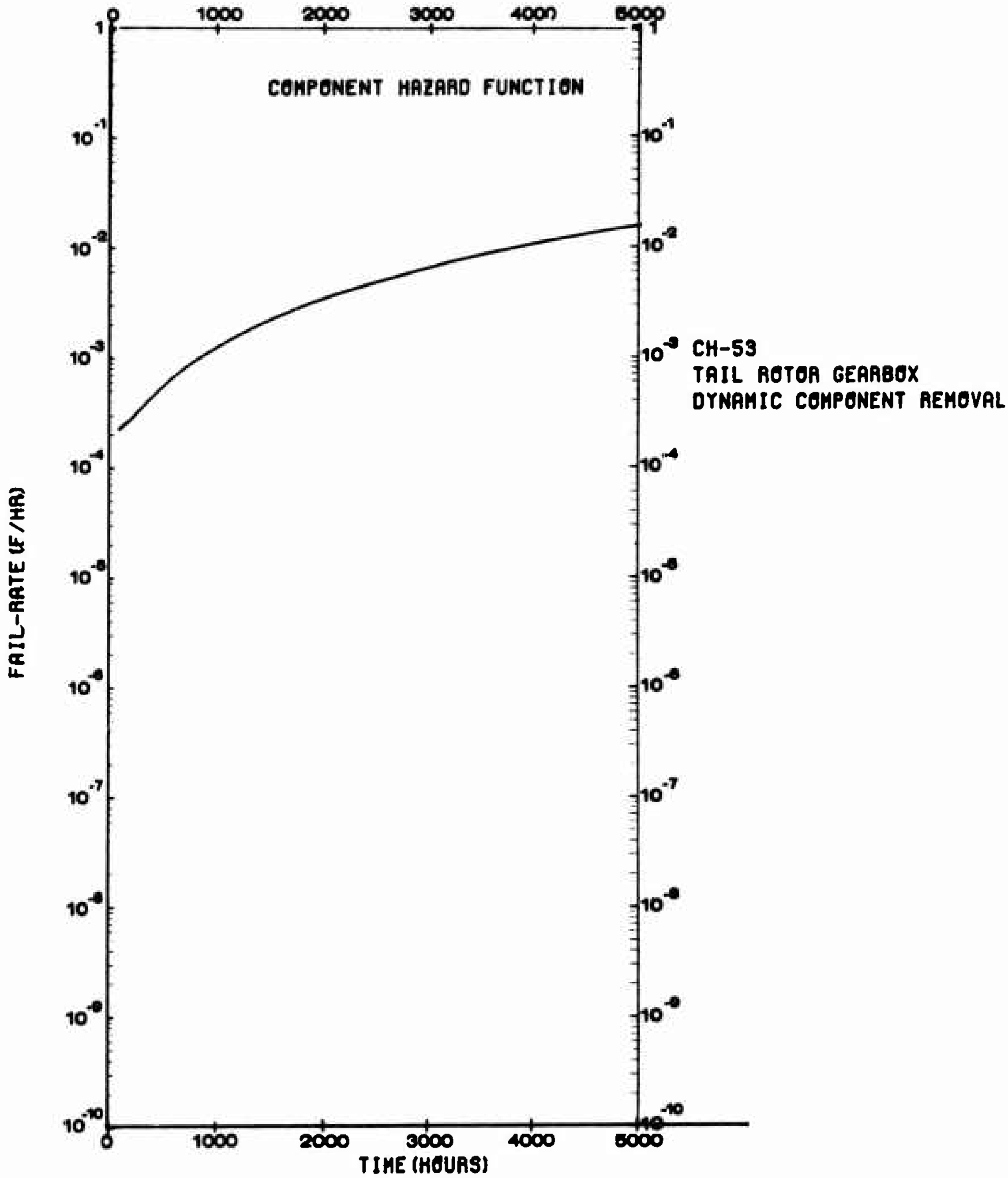

Figure 41. CH-53 Tail Rotor Gearbox Dynamic Component Removal Hazard Function.

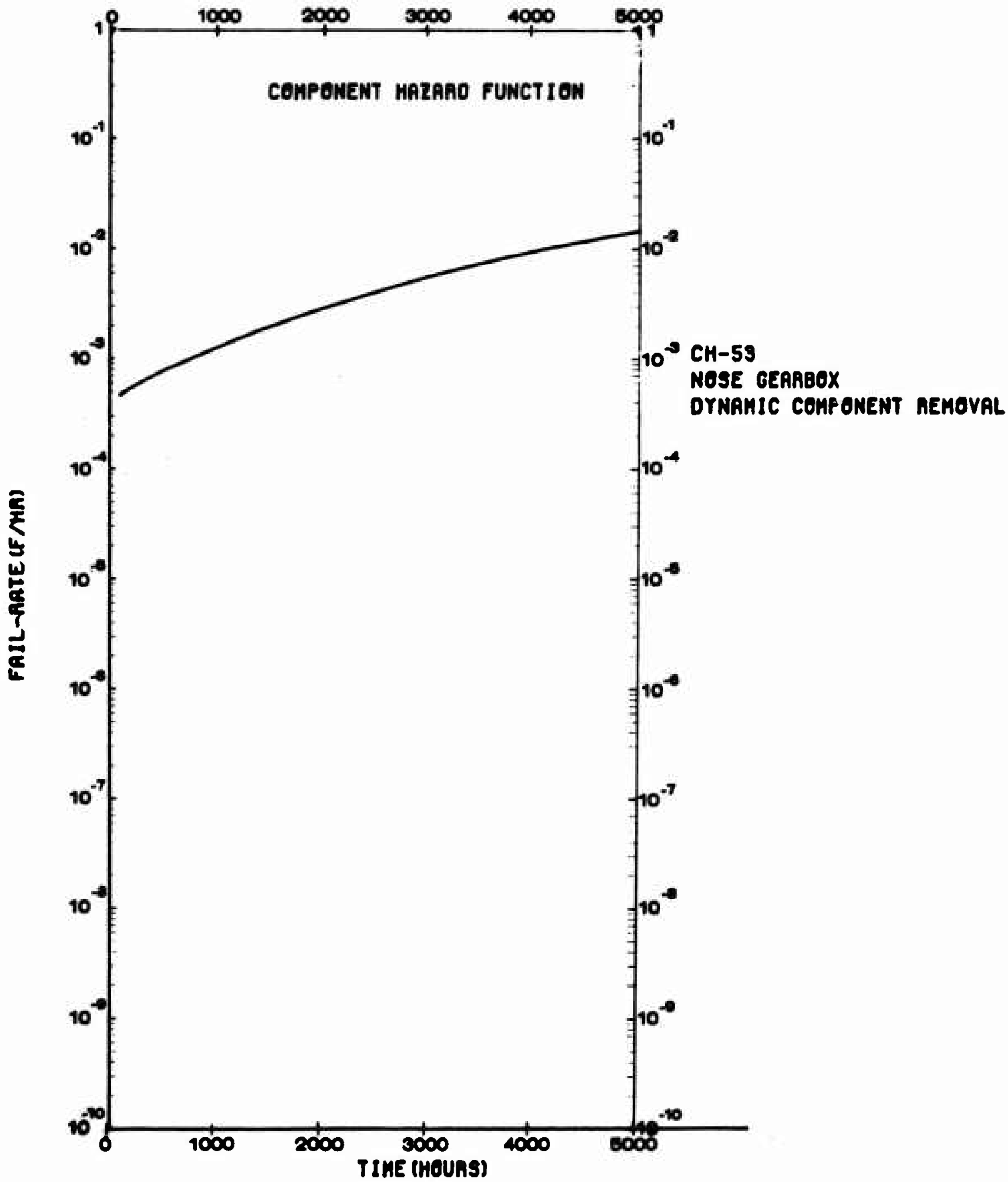

Figure 42. CH-53 Nose Gearbox Dynamic Component Removal Hazard Function.

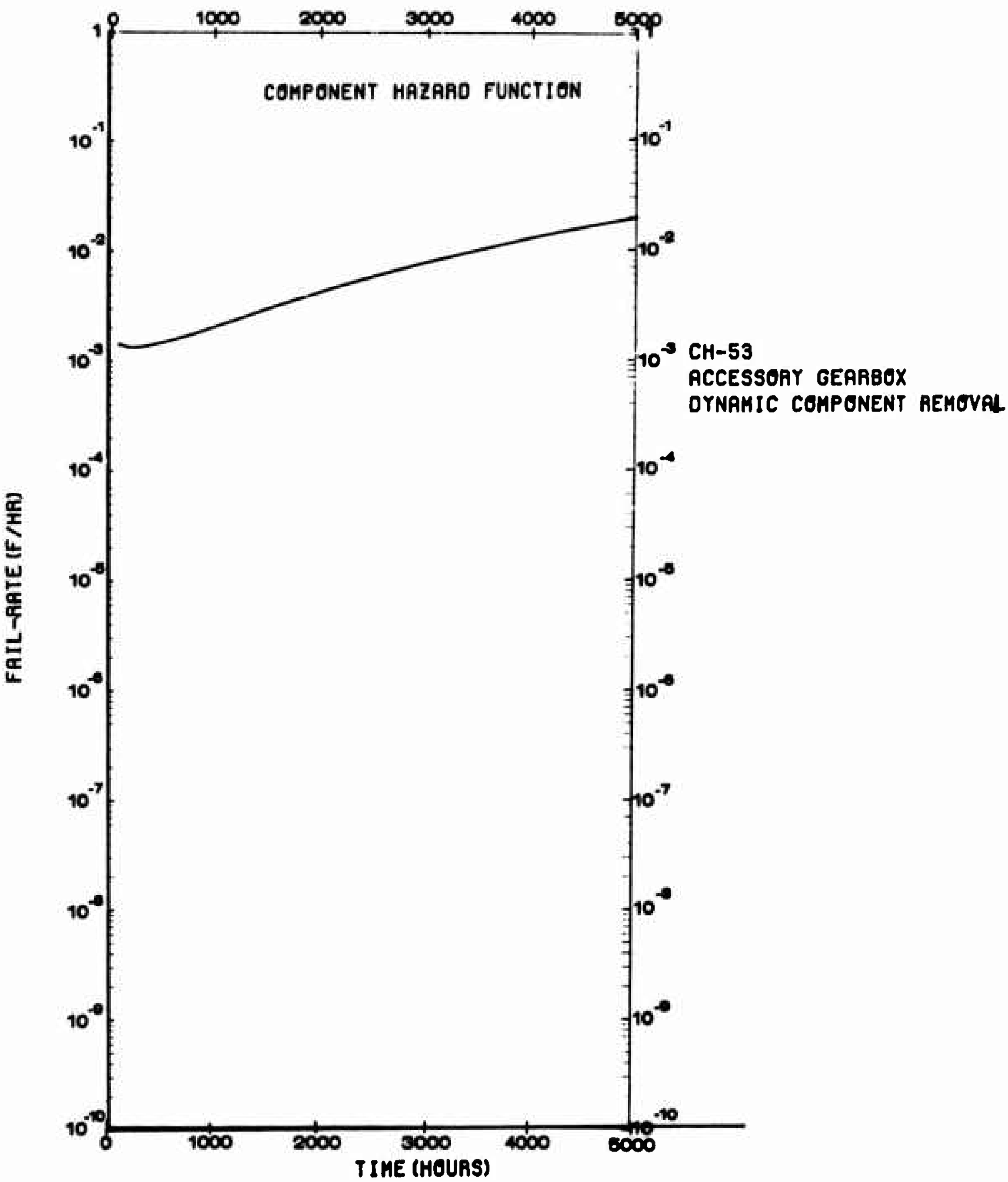

Figure 43. CH-53 Accessory Gearbox Dynamic Component Removal Hazard Function.

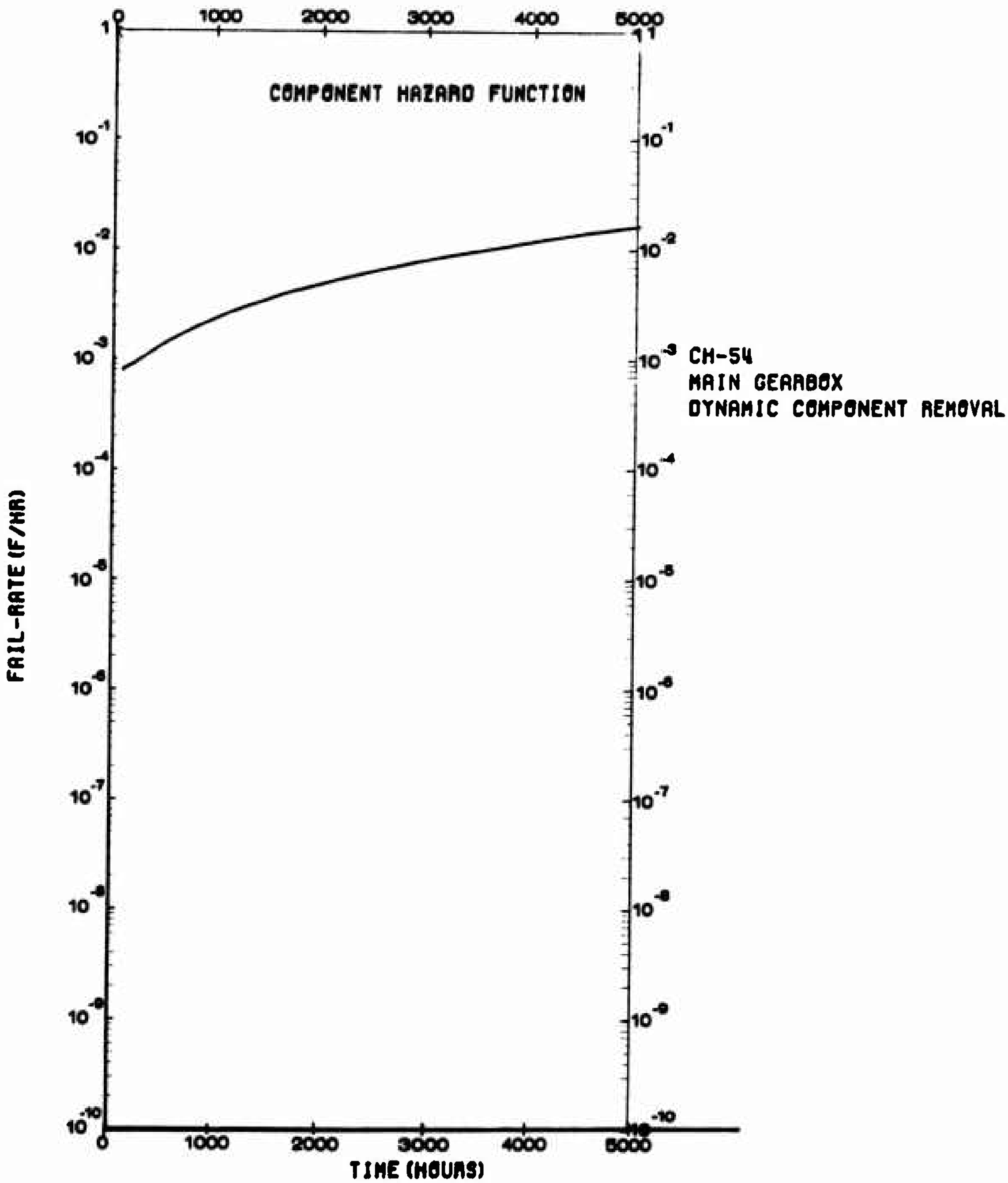

Figure 44. CH-54 Main Gearbox Dynamic Component Removal Hazard Function.

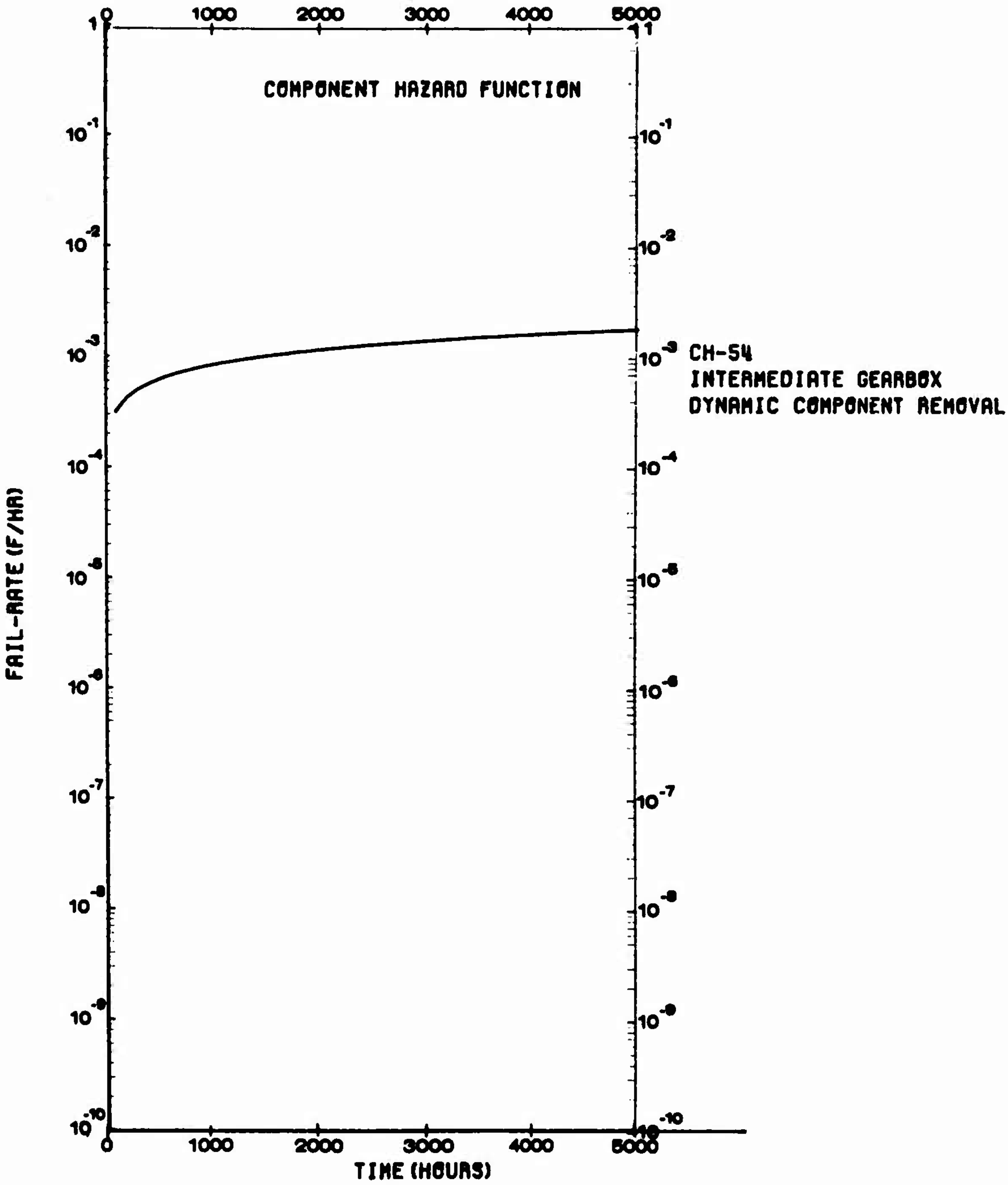

Figure 45. CH-54 Intermediate Dynamic Component Removal Hazard Function.

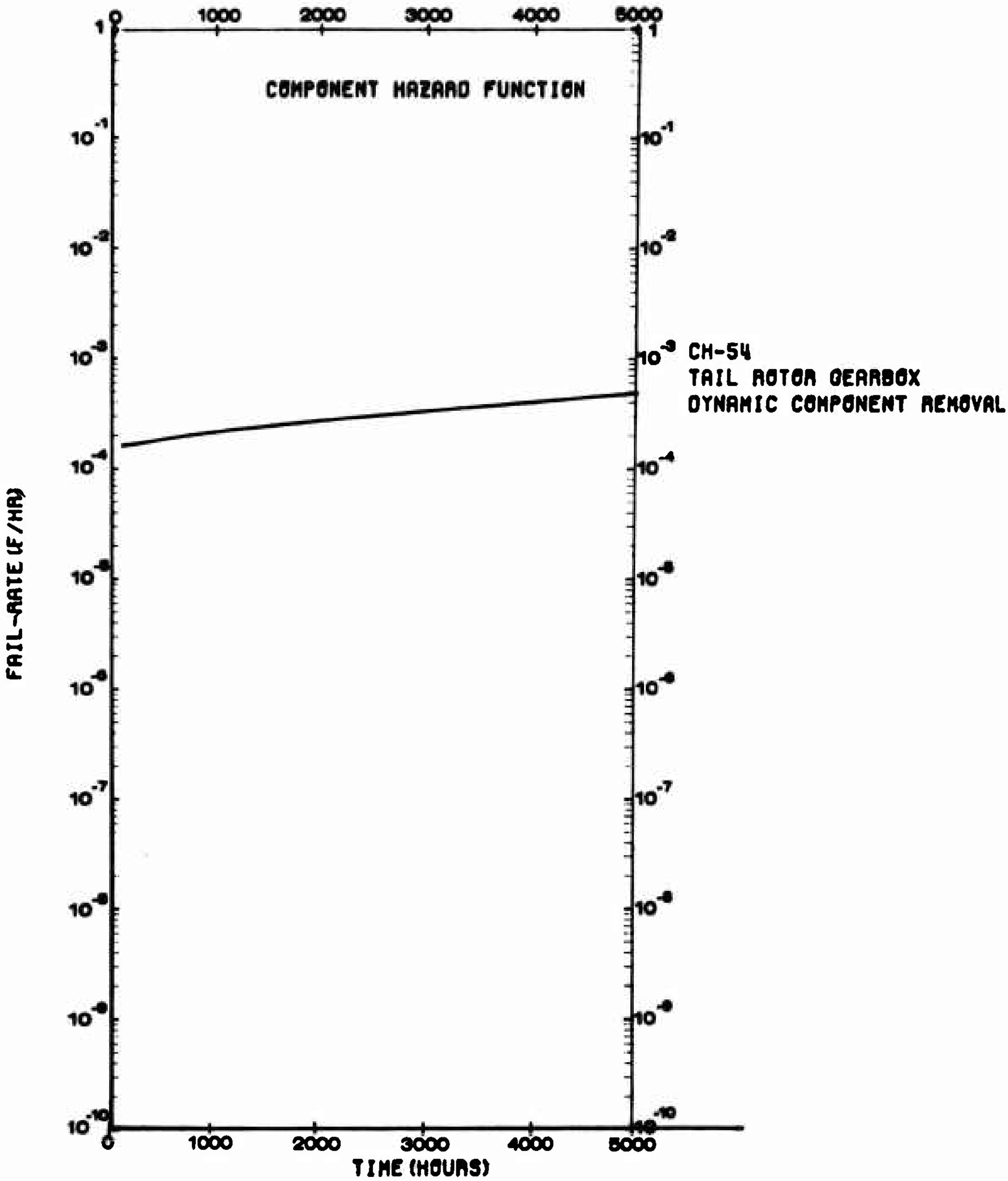

Figure 46. CH-54 Tail Rotor Dynamic Component Removal Hazard Function.

to distinguish between parts where subsequent failure is likely. Results could be very conservative. In fact, it is possible that parts deemed to have incipient failures could have continued to the next scheduled overhaul without any failure. Nevertheless, improvements can be made to substantially reduce this failure mode's impact if the gearbox were placed on-condition. Certainly, this is an area that should be monitored to see the impact of TBO extension.

Table 18 summarizes the generic component failure mode hazard functions that comprise each gearbox's dynamic component removal hazard function. Each hazard function is described by its shape and size parameters, β and θ. Failure modes that are significant generally have shape parameters greater than one and size parameters in the thousands of hours.

Failure modes which significantly affect aborts are generally the same ones which affect dynamic component removal failures. Figures 47 through 54 show the mission reliability failure hazard functions for the CH-53/54 gearbox. A comparison of these with the corresponding hazard function for dynamic component removal shows that curve shapes are generally the same. Table 19 shows the failure modes that significantly affect each hazard function at 5000 hours. Although percentages may change, there are very few new contributors over the ones given in Table 17. A notable exception is splines in the CH-54 main gearbox. The main reason for it is that some of the mission reliability failures were field repairable. As a result, additional failures were included in the mission reliability category that were not in the dynamic component removal failure category. The spline couplings responsible for the additional failures are those of the engine inputs. This coupling, unlike most of the other couplings, is not rigidly secured with a locknut, so floating allows for normal thermal expansion of the drive shaft.

While the CH-54 data allowed tracking of mission reliability failures that were field repairable, the CH-53 data did not. Mission reliability failures reported for the CH-53 were those that also resulted in dynamic component removal. As a result, hazard functions for mission reliability failures such as of shaft seal leakage may be optimistic.

Table 20 summarizes the generic component failure mode hazard functions that comprise each gearbox's mission reliability hazard function. Each hazard function is described by its shape and size parameters, β and θ Failure modes that are significant generally have shape parameters that are greater than one and size parameters in the higher thousands of hours.

Safety-of-flight hazard functions are generally relatively constant. Figures 55 through 60 show the safety-of-flight hazard functions. One or two failure modes are usually responsible for the increase that exists, as shown by Table 21. The hazard functions shown should be viewed as conservative. No attempt was made to satisfy the boundary conditions implied by the safety record mentioned in Section 2.4 since there was inadequate information on gearbox operating times. Housing cracks and spline wear are the only failure modes which significantly affect gearbox safety-of-flight hazard function. Most housings are redundant structures, yet this analysis has cônservatively assumed that a safety of flight malfunction can occur with one crack. Furthermore, those housings where cracks have been observed are frequently inspected to further reduce the possibility of a critical fracture. Critical splines are well secured with a pretorqued locknut, which in turn is prevented from loosening and backing off of the shaft by another locking device. While it may be questionable as to why these modes have remained in the safety-of-flight category, further improvements are suggested in Section 3 which make these failure modes more remote.

Table 22 summarizes the generic component failure mode hazard functions that comprise each gearbox's safety-of-flight hazard function. Each hazard function is described by its shape and size parameter.

TABLE 18. DYNAMIC COMPONENT REMOVAL FAILURE HAZARD FUNCTION PARAMETERS

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
CH-54 Main	Spiral Bevel Gear	Excess Wear	1.40	$.1928 \times 10^6$
		Spalling	1.00	$.8176 \times 10^6$
		Scoring	1.00	$.4886 \times 10^6$
		Tooth Fracture	1.00	$.4886 \times 10^6$
		Web/Shaft Crack	1.00	$.4886 \times 10^6$
	Spur Gear	Excess Wear	1.30	$.5516 \times 10^5$
		Spalling	1.00	$.2393 \times 10^7$
		Scoring	1.00	$.2393 \times 10^7$
		Tooth Fracture	1.00	$.2393 \times 10^7$
		Web/Shaft Crack	1.00	$.2393 \times 10^7$
	Spline	Wear, Fretting	1.33	$.6143 \times 10^4$
	Ball Bearing	Cage Fracture	1.00	$.6700 \times 10^4$
		Spalling	1.30	$.1172 \times 10^6$
		Smearing	1.00	$.1196 \times 10^8$
		Excess Wear	1.10	$.2231 \times 10^7$
	Lock Ring	Fracture	1.00	$.1895 \times 10^7$
	Bearing Retainer	Crack, Shear	.98	$.2165 \times 10^5$
	Shaft	Crack	1.00	$.6182 \times 10^7$
		Spline Wear	1.50	$.1979 \times 10^6$
			1.20	$.2964 \times 10^9$
	Roller Bearing	Cage Fracture	1.00	$.4088 \times 10^7$
		Spalling	1.30	$.6895 \times 10^5$
		Smearing	1.00	$.4088 \times 10^7$
		Excess Wear	1.10	$.1116 \times 10^7$
	Tapered Roller Bearing	Cage Fracture	1.00	$.3490 \times 10^7$
		Spalling	2.40	$.1021 \times 10^5$
		Smearing	1.00	$.3959 \times 10^5$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
CH-54 Main	Tapered Roller Bearing	Excess Wear	1.30	$.1310 \times 10^6$
	Thrust Washer	Excess Wear	2.70	$.4235 \times 10^4$
	FWU Cam	Spline Wear	1.20	$.1204 \times 10^9$
		Spring Seal Fracture	1.00	$.8176 \times 10^7$
	FWU Roller	Spalling	1.60	$.7633 \times 10^6$
		Excess Wear	2.64	$.1596 \times 10^4$
		Brinnelling	1.00	$.7778 \times 10^7$
	Spring	Fracture	1.00	$.4088 \times 10^7$
	Nut	Loose	1.70	$.4946 \times 10^5$
	"O" Ring	Leakage	.79	$.2848 \times 10^5$
	Shaft Seal	Leakage	1.95	$.1854 \times 10^4$
	Oil Pump		.63	$.2480 \times 10^8$
	Housing	Crack	2.38	$.2352 \times 10^5$
	Plate Assembly	Crack	1.00	$.1197 \times 10^7$
	FWU Cage	Cage Failure	1.76	$.2094 \times 10^4$
		Excess Wear	1.10	$.2231 \times 10^7$
	Oil Lets	Clogging	.64	$.4359 \times 10^5$
	Bolts	Shear	1.00	$.3031 \times 10^5$
	Flange	Fracture	1.00	$.8176 \times 10^7$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
CH-54 Intermediate	Spiral Bevel Gear	Excess Wear	1.40	$.9473 \times 10^6$
		Spalling	1.00	$.2991 \times 10^6$
		Scoring	1.00	$.2991 \times 10^6$
		Tooth Fracture	1.00	$.2991 \times 10^6$
		Web/Shaft Crack	1.00	$.2991 \times 10^6$
	Tapered Roller Bearing	Cage Fracture	1.00	$.2991 \times 10^6$
		Spalling	1.21	$.1276 \times 10^5$
		Smearing	1.00	$.2991 \times 10^6$
		Excess Wear	1.10	$.9793 \times 10^6$
	Spline	Wear, Fretting	1.50	$.5964 \times 10^5$
	Nut	Loose	1.10	$.2849 \times 10^6$
	"O" Ring	Leakage	.74	$.2600 \times 10^8$
	Lip Seal	Leakage	1.40	$.2289 \times 10^4$
	Housing	Crack	1.59	$.2747 \times 10^4$
	Roller Bearing	Cage Fracture	1.00	$.2105 \times 10^8$
		Spalling	1.30	$.2417 \times 10^5$
		Smearing	1.00	$.1551 \times 10^7$
		Excess Wear	1.10	$.4985 \times 10^7$
	Clip (Bearing) Retainer	Fracture	1.00	$.2770 \times 10^7$
	Snap Ring	Fracture	1.00	$.2770 \times 10^7$
	Bolts	Shear	1.00	$.3324 \times 10^7$
	Oil Pump	Zero Outlet Pressure	0.63	$.2480 \times 10^8$
	Roller Bearing	Cage Fracture	1.00	$.2105 \times 10^8$
		Spalling	1.30	$.2407 \times 10^5$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Roller Bearing (Cont'd.)	Smearing	1.00	$.1551 \times 10^{7}$
		Excess Wear	1.10	$.4985 \times 10^{7}$
CH-54 Tail Rotor	Spiral Bevel Gear	Excess Wear	1.40	$.1930 \times 10^{6}$
		Spalling	1.00	$.8053 \times 10^{6}$
		Scoring	1.00	$.8053 \times 10^{6}$
		Tooth Fracture	1.00	$.8053 \times 10^{6}$
		Web/Shaft Crack	1.00	$.8053 \times 10^{6}$
	Ball Bearing	Cage Fracture	1.00	$.5107 \times 10^{8}$
		Spalling	1.30	$.3557 \times 10^{6}$
		Smearing	1.00	$.5304 \times 10^{7}$
		Excess Wear	1.10	$.1649 \times 10^{7}$
	Tapered Roller Bearing	Cage Fracture	1.00	$.3732 \times 10^{7}$
		Spalling	1.30	$.3755 \times 10^{6}$
		Smearing	1.00	$.3732 \times 10^{7}$
		Excess Wear	1.10	$.8391 \times 10^{7}$
	Roller Bearing	Cage Fracture	1.00	$.4911 \times 10^{7}$
		Spalling	1.30	$.6188 \times 10^{5}$
		Smearing	1.00	$.4911 \times 10^{7}$
		Excess Wear	1.10	$.6286 \times 10^{6}$
	Bearing Retainer	Fracture	1.00	$.4911 \times 10^{7}$
	Spline	Wear, Fretting	1.50	$.6188 \times 10^{5}$
	Shaft	Crack	1.00	$.4911 \times 10^{8}$
	Nut	Loose	1.00	$.6285 \times 10^{8}$
	"O" Ring	Leakage	0.74	$.1231 \times 10^{10}$
	Lip Seal	Leakage	.44	$.3273 \times 10^{7}$
			1.40	$.1930 \times 10^{5}$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Pitch Change Control Shaft Anti-rotation Groove	Fretting	2.86	$.7365 \times 10^4$
	Bushing	Excess Wear	1.04	$.2286 \times 10^5$
	Housing	Crack	1.29	$.6932 \times 10^4$
CH-53 Main	Spiral Bevel Gear	Excess Wear	1.40	$.8921 \times 10^5$
		Spalling	1.00	$.2792 \times 10^6$
		Scoring	1.00	$.1673 \times 10^7$
		Tooth Fracture	1.00	$.1673 \times 10^7$
		Web/Shaft Fracture	1.00	$.1673 \times 10^7$
	Spur Gear	Excess Wear	1.30	$.2055 \times 10^5$
		Spalling	1.00	$.6920 \times 10^6$
		Scoring	1.00	$.6920 \times 10^6$
		Tooth Fracture	.71	$.3883 \times 10^5$
		Web/Shaft Crack	1.00	$.6920 \times 10^6$
	Ball Bearing	Cage Fracture	1.00	$.2991 \times 10^7$
		Spalling	1.30	$.3585 \times 10^5$
		Smearing	1.00	$.2991 \times 10^7$
		Excess Wear	1.84	$.2654 \times 10^4$
		Brinnelling	1.00	$.2991 \times 10^7$
	Roller Bearing	Cage Fracture	1.00	$.1434 \times 10^7$
		Spalling	2.54	$.1337 \times 10^4$
		Smearing	1.00	$.1434 \times 10^7$
		Excess Wear	1.10	$.4332 \times 10^6$
	Tapered Roller Bearing	Cage Fracture	1.00	$.1434 \times 10^7$
		Spalling	2.40	$.7254 \times 10^4$
		Smearing	1.00	$.1434 \times 10^7$
		Excess Wear	1.30	$.6537 \times 10^5$
	Spline	Wear, Fretting	1.33	$.5918 \times 10^5$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Bearing Retainer Clip	Crack Shear	1.32	$.2994 \times 10^4$
	Thrust Washer	Excess Wear	2.70	$.4235 \times 10^4$
	"O" Ring	Leakage	.74	$.1584 \times 10^9$
	Shaft Seal	Leakage	0.66	$.5531 \times 10^5$
			1.08	$.1482 \times 10^6$
	Flange	Crack	1.00	$.1267 \times 10^7$
	FWU Housing	Crack	1.00	$.1669 \times 10^7$
	FWU Roller	Spalling	1.60	$.3616 \times 10^6$
		Excess Wear	1.10	$.2332 \times 10^7$
		Brinnelling	1.00	$.2442 \times 10^6$
	FWU Cage	Excess Wear	1.10	$.8510 \times 10^6$
		Cage Fracture	1.76	$.1330 \times 10^6$
	Spring	Fracture	1.00	$.1262 \times 10^7$
	Shaft	Crack	1.00	$.9970 \times 10^5$
	Housing	Crack	2.83	$.1236 \times 10^5$
	Plate Assembly	Crack	1.00	$.2442 \times 10^6$
	Oil Pump	Zero Outlet Pressure	0.63	$.2480 \times 10^8$
	Oil Jets	Clogging	0.64	$.4875 \times 10^7$
	Nuts	Loose	1.70	$.1424 \times 10^4$
CH-53 Intermediate	Spiral Bevel Gear	Excess Wear	1.40	$.8852 \times 10^6$
		Spalling	1.00	$.4116 \times 10^5$
		Scoring	1.00	$.2706 \times 10^6$
		Tooth Fracture	1.00	$.2706 \times 10^6$
		Web/Shaft Crack	1.00	$.2706 \times 10^6$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Tapered Roller Bearing	Cage Fracture	1.00	$.2640 \times 10^6$
		Spalling	.68	$.1498 \times 10^6$
		Spalling	2.43	$.2609 \times 10^4$
		Smearing	0.84	$.5348 \times 10^5$
		Excess Wear	1.26	$.9905 \times 10^4$
	Spline	Excess Wear	1.50	$.3107 \times 10^5$
	Nuts	Loose	1.10	$.1683 \times 10^6$
	"O" Rings	Leakage	.74	$.1046 \times 10^{10}$
	Lip Seal	Leakage	.19	$.1848 \times 10^{10}$
			1.37	$.3349 \times 10^4$
	Housing	Crack	1.60	$.4613 \times 10^6$
CH-53 Tail Rotor	Spiral Bevel Gear	Excess Wear	1.40	$.2743 \times 10^6$
		Spalling	1.00	$.1318 \times 10^7$
		Scoring	1.00	$.1318 \times 10^7$
		Tooth Fracture	1.00	$.1318 \times 10^7$
		Web/Shaft Crack	1.00	$.1318 \times 10^7$
	Ball Bearing	Cage Fracture	1.00	$.8355 \times 10^8$
		Spalling	1.30	$.5194 \times 10^5$
		Smearing	1.00	$.8355 \times 10^8$
		Excess Wear	1.10	$.1317 \times 10^8$
	Roller Bearing	Cage Fracture	1.00	$.6106 \times 10^7$
		Spalling	1.30	$.5483 \times 10^6$
		Smearing	1.00	$.6106 \times 10^7$
		Excess Wear	1.10	$.1313 \times 10^8$
	Bushing	Excess	3.09	$.2240 \times 10^4$
	Bearing Retainer	Fracture	1.00	$.8033 \times 10^7$
	Spline	Wear, Fretting	1.50	$.8591 \times 10^5$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Tapered Roller Bearing	Cage Fracture	1.00	$.8355 \times 10^6$
		Spalling	1.20	$.2343 \times 10^7$
		Smearing	1.00	$.8676 \times 10^7$
		Excess Wear	1.00	$.2579 \times 10^7$
	Shaft	Crack	1.00	$.8033 \times 10^7$
	Nuts	Loose	1.10	$.7501 \times 10^6$
	"O" Ring	Leakage	.74	$.2170 \times 10^8$
	Lip Seals	Leakage	.68	$.2777 \times 10^5$
	Pitch Change Control Rod Antirotation Groove	Fretting	2.86	$.2631 \times 10^4$
	Housing	Crack	2.19	$.1737 \times 10^4$
CH-53 Nose	Spiral Bevel Gear	Excess Wear	1.43	$.2272 \times 10^5$
		Spalling, Pitting	1.00	$.4115 \times 10^5$
		Scoring	1.00	$.6272 \times 10^8$
		Tooth Fracture	1.84	$.1164 \times 10^5$
		Web/Shaft Crack	1.91	$.6841 \times 10^5$
	Spur Gear	Excess Wear	3.19	$.1954 \times 10^4$
		Spalling, Pitting	1.00	$.6278 \times 10^8$
		Scoring	1.00	$.6278 \times 10^8$
		Tooth Fracture	1.00	$.6278 \times 10^8$
		Web/Shaft Crack	1.00	$.6278 \times 10^8$
	Ball Bearing	Cage Fracture	1.64	$.8795 \times 10^4$
		Spalling	0.69	$.6275 \times 10^6$
		Smearing	1.00	$.2466 \times 10^6$
		Excess Wear	0.75	$.2292 \times 10^6$
		Spalling	1.30	$.3046 \times 10^6$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Roller Bearing	Cage Fracture	1.00	$.6278 \times 10^{8}$
		Spalling	3.12	$.1492 \times 10^{5}$
		Smearing	1.00	$.6278 \times 10^{8}$
		Excess Wear	1.20	$.3355 \times 10^{8}$
	Tapered Roller Bearing	Cage Fracture	0.99	$.2221 \times 10^{5}$
		Spalling	3.12	$.2527 \times 10^{5}$
		Smearing	0.65	$.1001 \times 10^{7}$
		Excess Wear	1.17	$.1325 \times 10^{7}$
	Spline	Wear, Fretting	1.54	$.1940 \times 10^{4}$
			1.23	$.6000 \times 10^{7}$
			1.15	$.2900 \times 10^{10}$
	Nuts	Loose	1.73	$.1350 \times 10^{5}$
	Bearing Retainer	Fracture	1.56	$.1135 \times 10^{5}$
	Clip	Fracture	0.98	$.6910 \times 10^{8}$
	Shaft Seal	Leakage	1.08	$.1727 \times 10^{5}$
	"O" Rings	Leakage	0.74	$.3200 \times 10^{5}$
	Pulley Drive	Crack	1.00	$.6278 \times 10^{8}$
	Fan Pulley	V Groove Wear	2.77	$.1695 \times 10^{5}$
	Square Aperture	Excess Wear	1.67	$.4208 \times 10^{6}$
	Quill Shaft	Crack	1.00	$.6278 \times 10^{8}$
		Excess Wear	1.24	$.1416 \times 10^{10}$
	Oil Pump	Zero Outlet Pressure	0.63	$.2480 \times 10^{8}$
	Housing	Crack	2.34	$.3617 \times 10^{5}$
	Oil Jets	Clogging	0.67	$.1656 \times 10^{10}$
	Flange	Crack	1.00	$.6278 \times 10^{8}$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
CH-53 Accessory	Spur Gear	Excess Wear	1.33	$.6041 \times 10^4$
		Spalling	1.00	$.4433 \times 10^6$
		Scoring	1.00	$.4443 \times 10^6$
		Tooth Fracture	1.00	$.4443 \times 10^6$
		Web/Shaft Crack	1.00	$.4443 \times 10^6$
	Ball Bearing	Cage Fracture	1.00	$.4877 \times 10^7$
		Spalling	1.26	$.1029 \times 10^5$
		Smearing	1.00	$.4877 \times 10^7$
		Excess Wear	1.10	$.2375 \times 10^7$
	Spline	Wear, Fretting	3.07	$.1701 \times 10^4$
	Nut	Loose	1.62	$.7338 \times 10^4$
	Lock Ring	Fracture	1.01	$.1987 \times 10^5$
	Shaft Seal	Leakage	1.14	$.1922 \times 10^5$
	"O" Ring	Leakage	0.74	$.4186 \times 10^{10}$
	FWU Roller	Spalling	1.60	$.7526 \times 10^4$
		Excess Wear	0.79	$.3641 \times 10^5$
		Brinnelling	1.00	$.1897 \times 10^7$
		Excess Wear	1.10	$.3770 \times 10^7$
	FWU Cage	Excess Wear	1.10	$.3770 \times 10^7$
		Fracture	0.91	$.2869 \times 10^5$
	Thrust Washer	Excess Wear	3.00	$.9082 \times 10^4$
	Spring	Fracture	1.00	$.6502 \times 10^8$
	Shaft	Crack	1.00	$.4842 \times 10^4$
	Roller Bearing	Cage Fracture	1.00	$.2059 \times 10^8$
		Spalling	1.13	$.2003 \times 10^5$
		Smearing	1.00	$.2059 \times 10^8$
		Excess Wear	1.10	$.4900 \times 10^8$

TABLE 18. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Oil Pump	Zero Outlet Pressure	0.46	$.1542 \times 10^7$
	Oil Jet	Clogging	0.64	$.2201 \times 10^8$
	Housing	Crack	1.60	$.2719 \times 10^4$

TABLE 19. SIGNIFICANT MISSION RELIABILITY FAILURE MODES

Aircraft	Gearbox	Generic Failure Mode	Percentage Contribution to G/B HZD FN.*
CH-54	Main	Spline Coupling Fretting Wear	31
		FWU Roller Excess Wear	30
		"O" Ring Leakage	6
		FWU Roller Spalling	5
		FWU Cage Fracture	4
	Interme-diate	No Significantly Increasing Failure Mode.	
	Tail Rotor	Housing Crack	21
		Pitch Change Control Rod Antirotation Groove Wear	28
		Lip Seal Leakage	9
		Bushing Wear	9
CH-53	Main	Clip Wear	58
		Bolts Shear	32
	Interme-diate	No Significantly Increasing Failure Mode.	
	Tail Rotor	Pitch Change Control Rod Antirotation Groove Wear	24
		Bushing Wear	70
	Nose	Spur Gear Wear	79
		Tapered Roller Bearing Spalling	10
	Accessory	Spline Coupling Wear	55%
		Housing Crack	26%

* At 5000 Hours.

TABLE 20. MISSION RELIABILITY HAZARD FUNCTION PARAMETERS

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
CH-54 Main	Spiral Bevel Gear	Excess Wear	1.40	$.1928 \times 10^6$
		Spalling	1.00	$.8176 \times 10^6$
		Scoring	1.00	$.4886 \times 10^7$
		Tooth Fracture	1.00	$.4886 \times 10^7$
		Web/Shaft Crack	1.00	$.4886 \times 10^7$
	Spur Gear	Excess Wear	1.30	$.5516 \times 10^5$
		Spalling	1.00	$.2393 \times 10^7$
		Scoring	1.00	$.2393 \times 10^7$
		Tooth Fracture	1.00	$.2393 \times 10^7$
		Web/Shaft Crack	1.00	$.2393 \times 10^7$
	Spline	Wear, Fretting	1.76	$.2881 \times 10^4$
	Ball Bearing	Cage Fracture	1.00	$.1344 \times 10^5$
		Spalling	1.30	$.1172 \times 10^6$
		Smearing	1.00	$.1196 \times 10^7$
		Excess Wear	1.10	$.2231 \times 10^7$
	Lock Ring	Fracture	1.0	$.1895 \times 10^7$
	Bearing Retainer	Crack, Shear	0.98	$.1092 \times 10^6$
	Shaft	Crack	1.00	$.6182 \times 10^7$
		Spline Wear	1.50	$.1979 \times 10^6$
			1.20	$.2964 \times 10^9$
		Square Hole Enlargement	1.70	$.5995 \times 10^6$
	Roller Bearing	Cage Fracture	1.00	$.4088 \times 10^7$
		Spalling	1.30	$.6395 \times 10^5$
		Smearing	1.00	$.4188 \times 10^7$
		Excess Wear	1.10	$.1116 \times 10^7$
	Tapered Roller Bearing	Cage Fracture	1.00	$.3490 \times 10^7$
		Spalling	2. 1	$.1021 \times 10^5$
		Smearing	1.0	$.3959 \times 10^5$

TABLE 20. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Tapered Roller Bearing	Excess Wear	1.3	$.1310 \times 10^{6}$
	Thrust Washer	Excess Wear	2.7	$.5475 \times 10^{4}$
	FWU Cam	Spline Wear	1.2	$.1204 \times 10^{9}$
		Spring Seat Fracture	1.0	$.8176 \times 10^{7}$
	FWU Roller	Spalling	1.6	$.7633 \times 10^{4}$
		Excess Wear	2.64	$.4127 \times 10^{4}$
		Brinnelling	1.00	$.7778 \times 10^{7}$
	Spring	Fracture	1.00	$.6182 \times 10^{7}$
	Nut	Loose	1.70	$.4946 \times 10^{5}$
	"O" Ring	Leakage	1.27	$.6364 \times 10^{4}$
	Shaft Seal	Leakage	0.77	$.1089 \times 10^{6}$
	Oil Pump	Zero Outlet Pressure	0.63	$.2480 \times 10^{8}$
	Housing	Crack	2.38	$.2352 \times 10^{5}$
	Plate Assembly	Crack	1.00	$.1197 \times 10^{7}$
	FWU Cage	Cage Fracture	1.76	$.9981 \times 10^{4}$
		Excess Wear	1.10	$.2231 \times 10^{7}$
	Oil Jets	Clogging	0.64	$.1819 \times 10^{7}$
	Bolts	Shear	1.00	$.6092 \times 10^{5}$
CH-54 Intermediate	Spiral Bevel Gear	Excess Wear	1.40	$.9473 \times 10^{5}$
		Spalling	1.00	$.2991 \times 10^{6}$
		Scoring	1.00	$.2991 \times 10^{6}$
		Tooth Fracture	1.00	$.2991 \times 10^{6}$
		Web/Shaft Crack	1.00	$.2991 \times 10^{6}$

TABLE 20. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Tapered Roller	Cage Fracture	1.00	$.2991 \times 10^6$
		Spalling	1.21	$.1276 \times 10^5$
		Smearing	1.00	$.2991 \times 10^6$
		Excess Wear	1.10	$.9793 \times 10^6$
	Spline	Wear, Fretting	1.5	$.5964 \times 10^6$
	Nut	Loose	1.1	$.9793 \times 10^6$
	"O" Ring	Leakage	0.74	$.2600 \times 10^8$
	Lip Seal	Leakage	1.40	$.2129 \times 10^5$
	Housing	Crack	1.59	$.2500 \times 10^8$
	Roller Bearing	Cage Fracture	1.00	$.2105 \times 10^8$
		Spalling	1.30	$.2407 \times 10^5$
		Smearing	1.00	$.1551 \times 10^7$
		Excess Wear	1.10	$.4985 \times 10^7$
	Clip (Bearing) Retainer	Fracture	1.00	$.2770 \times 10^7$
	Snap Ring	Fracture	1.00	$.2770 \times 10^7$
	Bolts	Shear	1.00	$.2959 \times 10^5$
	Oil Pump	Zero Outlet Pressure	0.63	$.2480 \times 10^8$
CH-54 Tail Rotor	Spiral Bevel Gear	Excess Wear	1.40	$.1930 \times 10^6$
		Spalling	1.00	$.8053 \times 10^6$
		Scoring	1.00	$.8053 \times 10^6$
		Tooth Fracture	1.00	$.8053 \times 10^6$
		Web/Shaft Crack	1.00	$.8053 \times 10^6$
	Ball Bearing	Cage Fracture	1.00	$.5107 \times 10^8$
		Spalling	1.30	$.3557 \times 10^6$
		Smearing	1.00	$.5304 \times 10^7$
		Excess Wear	1.10	$.1649 \times 10^7$

TABLE 20. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	Θ (Hours)
	Tapered Roller Bearing	Cage Fracture	1.00	$.3732 \times 10^7$
		Spalling	1.30	$.3755 \times 10^6$
		Smearing	1.00	$.3732 \times 10^7$
		Excess Wear	1.10	$.8391 \times 10^7$
	Roller Bearing	Cage Fracture	1.00	$.4911 \times 10^7$
		Spalling	1.30	$.6188 \times 10^5$
		Smearing	1.00	$.4911 \times 10^7$
		Excess Wear	1.10	$.6286 \times 10^6$
	Bearing Retainer	Fracture	1.00	$.4911 \times 10^7$
	Spline	Wear, Fretting	1.50	$.6188 \times 10^5$
	Shaft	Crack	1.00	$.4911 \times 10^8$
	Nut	Loose	1.00	$.6285 \times 10^8$
	"O" Ring	Leakage	0.74	$.1231 \times 10^{10}$
	Lip Seal	Leakage	0.44	$.5437 \times 10^7$
			1.40	$.4650 \times 10^5$
	Pitch Change Control Shaft Antirotation Groove	Fretting	2.86	$.1280 \times 10^5$
	Bushing	Excess Wear	1.04	$.7485 \times 10^5$
	Housing	Crack	1.29	$.2728 \times 10^5$
CH-53 Main	Spiral Bevel Gear	Excess Wear	1.40	$.8921 \times 10^5$
		Spalling	1.00	$.2792 \times 10^6$
		Scoring	1.00	$.1673 \times 10^7$
		Tooth Fracture	1.00	$.1673 \times 10^7$
		Web/Shaft Fracture	1.00	$.1673 \times 10^7$
		FWU Housing Fracture	1.00	$.1669 \times 10^7$

TABLE 20. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Spur Gear	Excess Wear	1.30	$.2055 \times 10^5$
		Spalling	1.00	$.6920 \times 10^6$
		Scoring	1.00	$.6920 \times 10^6$
		Tooth Fracture	0.71	$.3884 \times 10^5$
		Web/Shaft Crack	1.00	$.6920 \times 10^6$
	Ball Bearing	Cage Fracture	1.00	$.2991 \times 10^7$
		Spalling	1.30	$.3985 \times 10^5$
		Smearing	1.00	$.2991 \times 10^7$
		Excess Wear	1.84	$.5198 \times 10^4$
		Brinnelling	1.00	$.2991 \times 10^7$
	Roller Bearing	Cage Fracture	1.00	$.1434 \times 10^7$
		Spalling	0.86	$.1816 \times 10^5$
		Smearing	1.00	$.1143 \times 10^7$
		Excess Wear	1.10	$.4332 \times 10^6$
	Tapered Roller Bearing	Cage Fracture	1.00	$.1434 \times 10^7$
		Spalling	2.40	$.9688 \times 10^4$
		Smearing	1.00	$.1434 \times 10^7$
		Excess Wear	1.30	$.6537 \times 10^5$
	Spline	Wear, Fretting	1.33	$.5918 \times 10^5$
	Bearing Retainer Clip	Crack Shear	1.32	$.4318 \times 10^4$
	Thrust Washer	Excess Wear	2.69	$.1747 \times 10^5$
	"O" Ring	Leakage	0.74	$.1584 \times 10^9$
	Shaft Seal	Leakage	0.66	$.5532 \times 10^5$
			1.08	$.1482 \times 10^6$
	Flange	Crack	1.00	$.1262 \times 10^7$
	FWU Rollers	Spalling	1.60	$.3616 \times 10^7$
		Excess Wear	1.10	$.2332 \times 10^7$
		Brinnelling	1.00	$.2442 \times 10^6$

TABLE 20. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	FWU Cage	Excess Wear	1.10	$.8510 \times 10^{6}$
		Cage Fracture	1.76	$.1330 \times 10^{5}$
	Spring	Fracture	1.00	$.1262 \times 10^{7}$
	Shaft	Crack	1.00	$.9970 \times 10^{5}$
	Housing	Crack	2.38	$.1206 \times 10^{5}$
	Plate Assembly	Crack	1.00	$.2442 \times 10^{6}$
	Oil Pump	Zero Outlet Pressure	0.63	$.2980 \times 10^{8}$
	Oil Jets	Clogging	0.64	$.4875 \times 10^{7}$
	Nuts	Loose	1.70	$.1424 \times 10^{4}$
CH-53 Intermediate	Spiral Bevel Gear	Excess Wear	1.40	$.8852 \times 10^{6}$
		Spalling	1.00	$.4116 \times 10^{5}$
		Scoring	1.00	$.2706 \times 10^{6}$
		Tooth Fracture	1.00	$.2706 \times 10^{6}$
		Web/Shaft Crack	1.00	$.2706 \times 10^{6}$
	Tapered Roller Bearing	Cage Fracture	1.0	$.2640 \times 10^{6}$
		Spalling	0.68	$.1498 \times 10^{6}$
		Spalling	2.43	$.2670 \times 10^{4}$
		Smearing	0.84	$.2329 \times 10^{6}$
		Excess Wear	1.26	$.1734 \times 10^{5}$
	Spline	Excess Wear	1.50	$.3107 \times 10^{5}$
	Nuts	Loose	1.10	$.1683 \times 10^{6}$
	"O" Rings	Leakage	0.74	$.1046 \times 10^{10}$
	Lip Seal	Leakage	0.19	$.2633 \times 10^{7}$
			1.37	$.3436 \times 10^{5}$
	Housing	Crack	1.60	$.1259 \times 10^{7}$

TABLE 20. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
CH-53 Tail Rotor	Spiral Bevel Gear	Excess Wear	1.40	$.2743 \times 10^7$
		Spalling	1.00	$.1318 \times 10^7$
		Scoring	1.00	$.1318 \times 10^7$
		Tooth Fracture	1.00	$.1318 \times 10^7$
		Web/Shaft Crack	1.00	$.1318 \times 10^7$
	Ball Bearing	Cage Fracture	1.00	$.8355 \times 10^8$
		Spalling	1.30	$.5194 \times 10^5$
		Smearing	1.00	$.8355 \times 10^8$
		Excess Wear	1.10	$.2579 \times 10^7$
	Roller Bearing	Cage Fracture	1.00	$.6106 \times 10^7$
		Spalling	1.30	$.5483 \times 10^7$
		Smearing	1.00	$.1313 \times 10^8$
		Excess Wear	1.10	$.8591 \times 10^5$
	Bushing	Excess	3.09	$.3350 \times 10^4$
	Bearing Retainer	Fracture	1.0	$.8033 \times 10^7$
	Spline	Wear, Fretting	1.5	$.8591 \times 10^5$
	Nuts	Loose	1.1	$.2645 \times 10^7$
	"O" Ring	Leakage	0.68	$.2170 \times 10^8$
	Pitch Change Control Rod Antirotation Groove	Fretting	2.86	$.4625 \times 10^4$
	Housing	Crack	2.19	$.7643 \times 10^4$
CH-53 Nose	Spiral Bevel Gear	Excess Wear	1.43	$.5374 \times 10^5$
		Spalling, Pitting	1.00	$.8275 \times 10^5$
		Scoring	1.00	$.6272 \times 10^8$
		Tooth Fracture	1.34	$.2272 \times 10^5$
		Web/Shaft Crack	1.91	$.6841 \times 10^5$

TABLE 20. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	Θ (Hours)
	Spur Gears	Excess Wear	3.19	$.2435 \times 10^4$
		Spalling, Pitting	1.00	$.6278 \times 10^8$
		Scoring	1.00	$.6278 \times 10^8$
		Tooth Fracture	1.00	$.6278 \times 10^8$
		Web/Shaft Crack	1.00	$.6278 \times 10^8$
	Ball Bearing	Cage Fracture	2.11	$.8696 \times 10^4$
		Spalling	0.69	$.3719 \times 10^7$
		Smearing	1.00	$.4951 \times 10^6$
		Excess Wear	0.75	$.1893 \times 10^7$
		Spalling	1.30	$.7765 \times 10^6$
	Roller Bearing	Cage Fracture	1.00	$.6278 \times 10^8$
		Spalling	3.12	$.1475 \times 10^5$
		Smearing	1.00	$.6278 \times 10^8$
		Excess Wear	1.20	$.3355 \times 10^6$
	Tapered Roller Bearing	Cage Fracture	0.99	$.2797 \times 10^6$
		Spalling	3.12	$.4680 \times 10^4$
		Smearing	0.65	$.6780 \times 10^8$
		Excess Wear	1.17	$.1625 \times 10^7$
	Spline	Wear, Fretting	1.54	$.3186 \times 10^4$
			1.24	$.1108 \times 10^9$
			1.15	$.5280 \times 10^{10}$
	Nuts	Loose	1.73	$.2750 \times 10^5$
	Bearing Retainer	Fracture	1.56	$.3700 \times 10^5$
	Shaft Seal	Leakage	1.08	$.1765 \times 10^6$
	"O" Rings	Leakage	0.74	$.3640 \times 10^5$
	Pulley Driven	Sheared	1.00	$.6278 \times 10^8$
	Fan Pulley	V-Groove Wear	2.77	$.1695 \times 10^5$
	Square Aperature	Excess Wear	1.67	$.6458 \times 10^7$

TABLE 20. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Quill Shaft	Crack	1.00	$.6278 \times 10^{8}$
		Excess Wear	1.24	$.2475 \times 10^{10}$
	Oil Pump	Zero Outlet Pressure	0.63	$.2480 \times 10^{8}$
	Housing	Crack	2.38	$.3617 \times 10^{5}$
	Oil Jets	Clogging	0.67	$.1656 \times 10^{10}$
	Flange	Crack	1.00	$.6278 \times 10^{8}$
CH-53 Accessory	Spur Gear	Excess Wear	1.33	$.2141 \times 10^{5}$
		Spalling	1.00	$.4493 \times 10^{6}$
		Scoring	1.00	$.4493 \times 10^{6}$
		Tooth Fracture	1.00	$.4493 \times 10^{6}$
		Web/Shaft Crack	1.00	$.4493 \times 10^{6}$
	Ball Bearing	Cage Fracture	1.00	$.4877 \times 10^{7}$
		Spalling	1.26	$.3620 \times 10^{5}$
		Smearing	1.00	$.4877 \times 10^{7}$
		Excess Wear	1.1	$.4476 \times 10^{7}$
	Spline	Wear, Fretting	3.07	$.4100 \times 10^{4}$
	Nut	Loose	1.12	$.2228 \times 10^{5}$
	Lock Ring	Fracture	1.01	$.9572 \times 10^{5}$
	Shaft Seal	Leakage	1.14	$.5674 \times 10^{5}$
	"O" Ring	Leakage	0.74	$.4187 \times 10^{6}$
	FWU Roller	Spalling	1.60	$.1621 \times 10^{5}$
		Excess Wear	0.79	$.3778 \times 10^{6}$
		Brinnelling	1.00	$.1897 \times 10^{7}$
		Excess Wear	1.10	$.3770 \times 10^{7}$
	FWU Cage	Excess Wear	1.10	$.3770 \times 10^{7}$
		Fracture	0.86	$.1646 \times 10^{6}$
	Thrust Washer	Excess Wear	3.00	$.9082 \times 10^{4}$

TABLE 20. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Spring	Fracture	1.00	$.6052 \times 10^8$
	Shaft	Crack	1.00	$.4842 \times 10^8$
	Roller Bearing	Cage Fracture	1.00	$.2059 \times 10^8$
		Spalling	1.13	$.5962 \times 10^5$
		Smearing	1.0	$.2059 \times 10^8$
		Excess Wear	1.10	$.4900 \times 10^7$
	Oil Pump	Zero Outlet Pressure	0.63	$.4495 \times 10^5$
	Oil Jet	Clogging	0.64	$.4360 \times 10^5$
	Housing	Crack	1.6	$.3659 \times 10^4$

TABLE 21. SIGNIFICANT POTENTIAL SAFETY-OF-FLIGHT FAILURE MODES

Aircraft	Gearbox	Generic Component Failure Mode[a]	Percentage Contribution to Gearbox Hazard Function[b]
CH-54	Main	Spline Fretting, Wear	67
	Intermediate	Spline Fretting, Wear	15
		Nuts Loose	8
		Housing Crack	1
	Tail Rotor	Spline Fretting, Wear	46
		Housing Crack	41
CH-53	Main	Spline Fretting, Wear	12
		Housing Crack	4
	Intermediate	Housing Crack	1
		Spline Fretting, Wear	84
	Tail Rotor	Housing Crack	25
		Spline Fretting, Wear	42

[a]Only failure modes with increasing hazard functions are listed.

[b]At 5000 Hours.

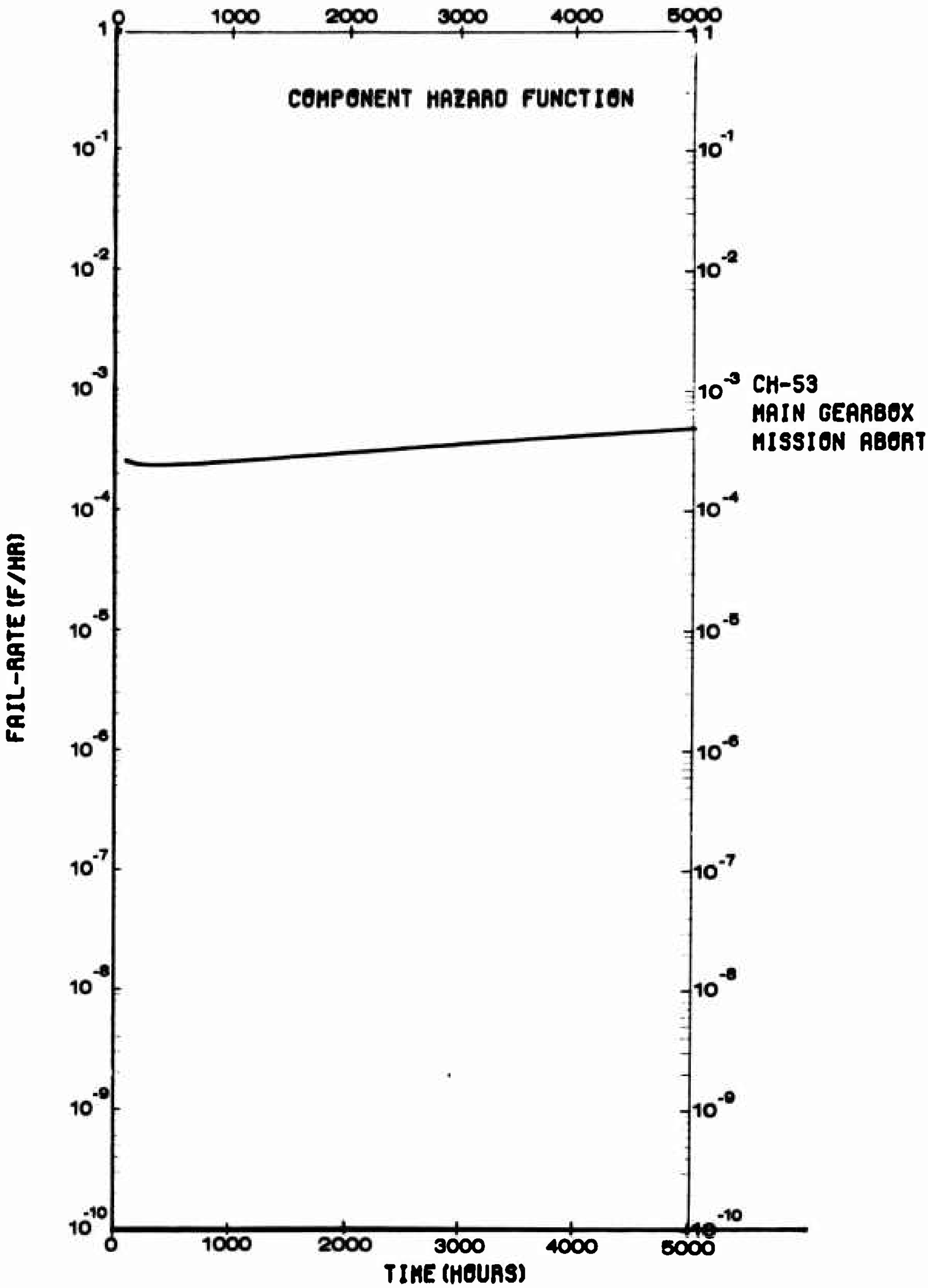

Figure 47. CH-53 Main Gearbox Mission Reliability Hazard Function.

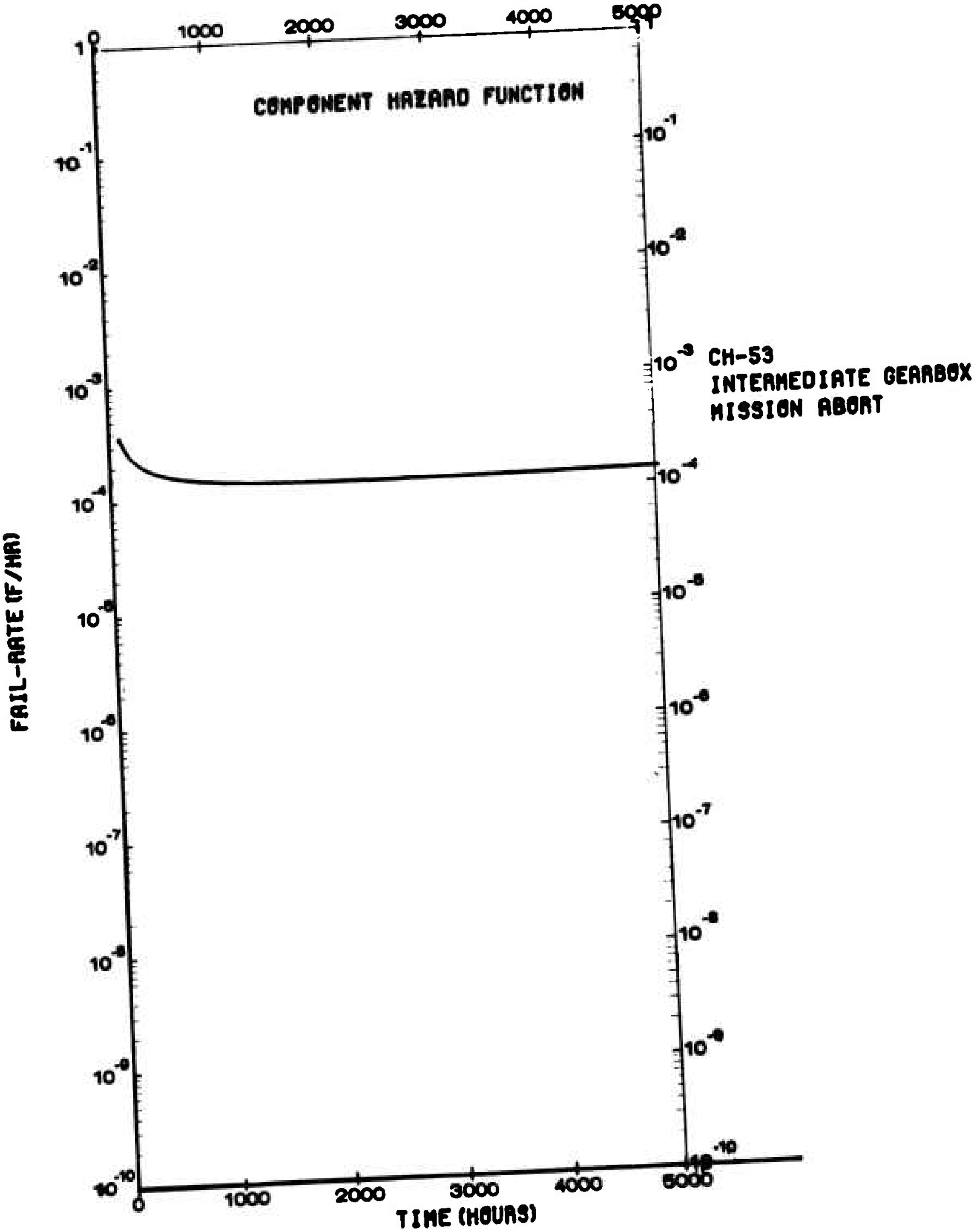

Figure 48. CH-53 Intermediate Gearbox Mission Reliability Hazard Function.

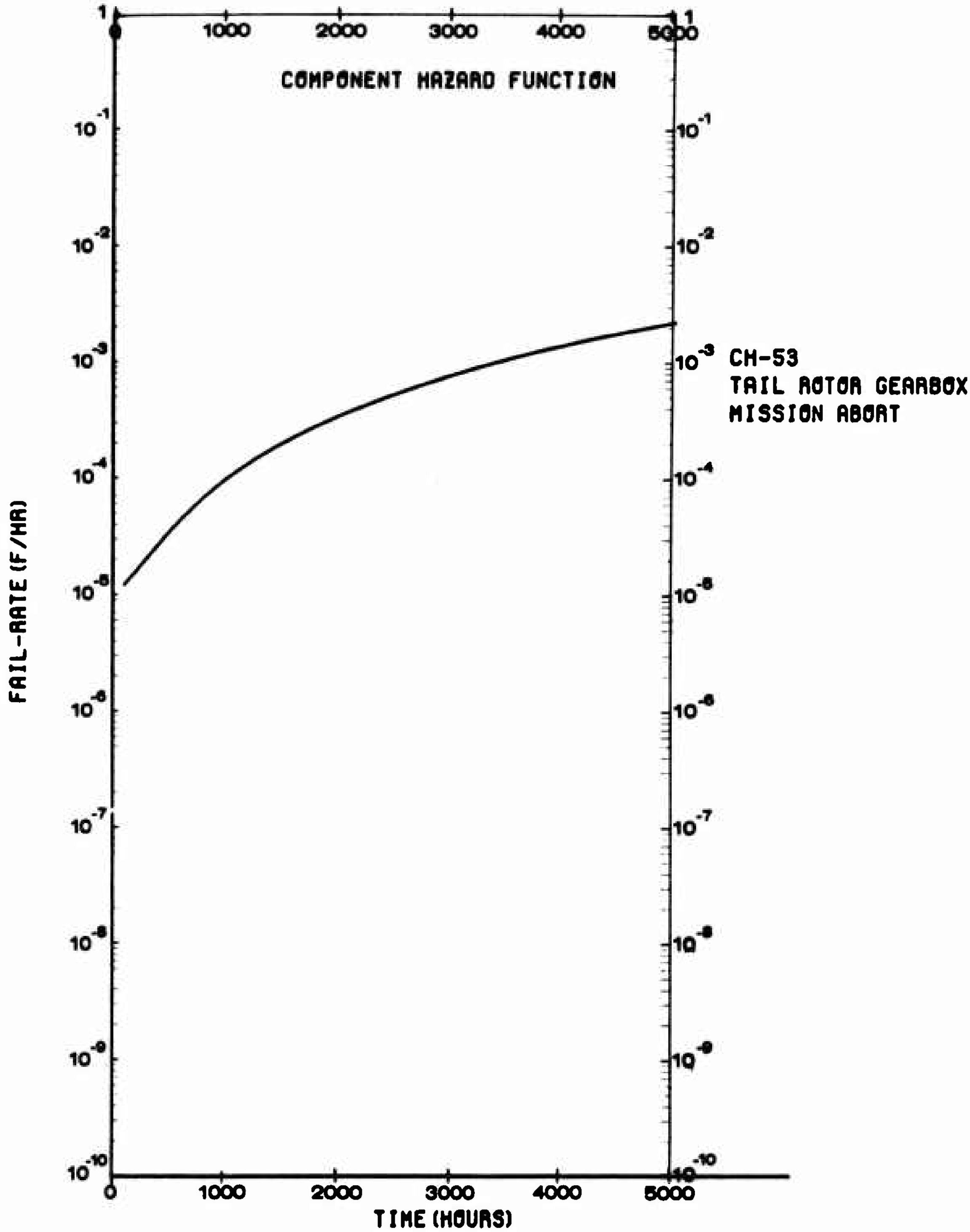

Figure 49. CH-53 Tail Rotor Gearbox Mission Reliability Hazard Function.

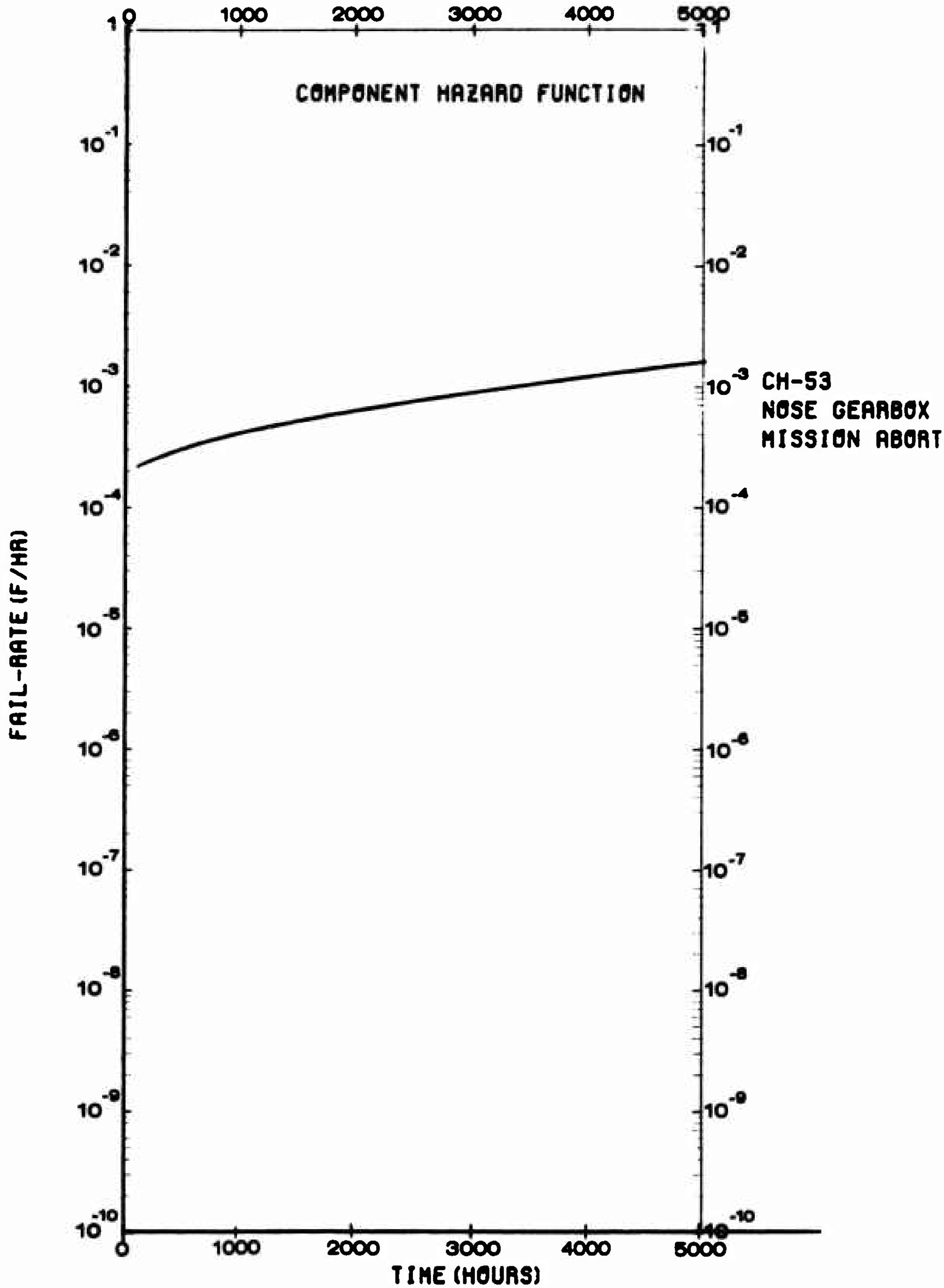

Figure 50. CH-53 Nose Gearbox Mission Reliability Hazard Function.

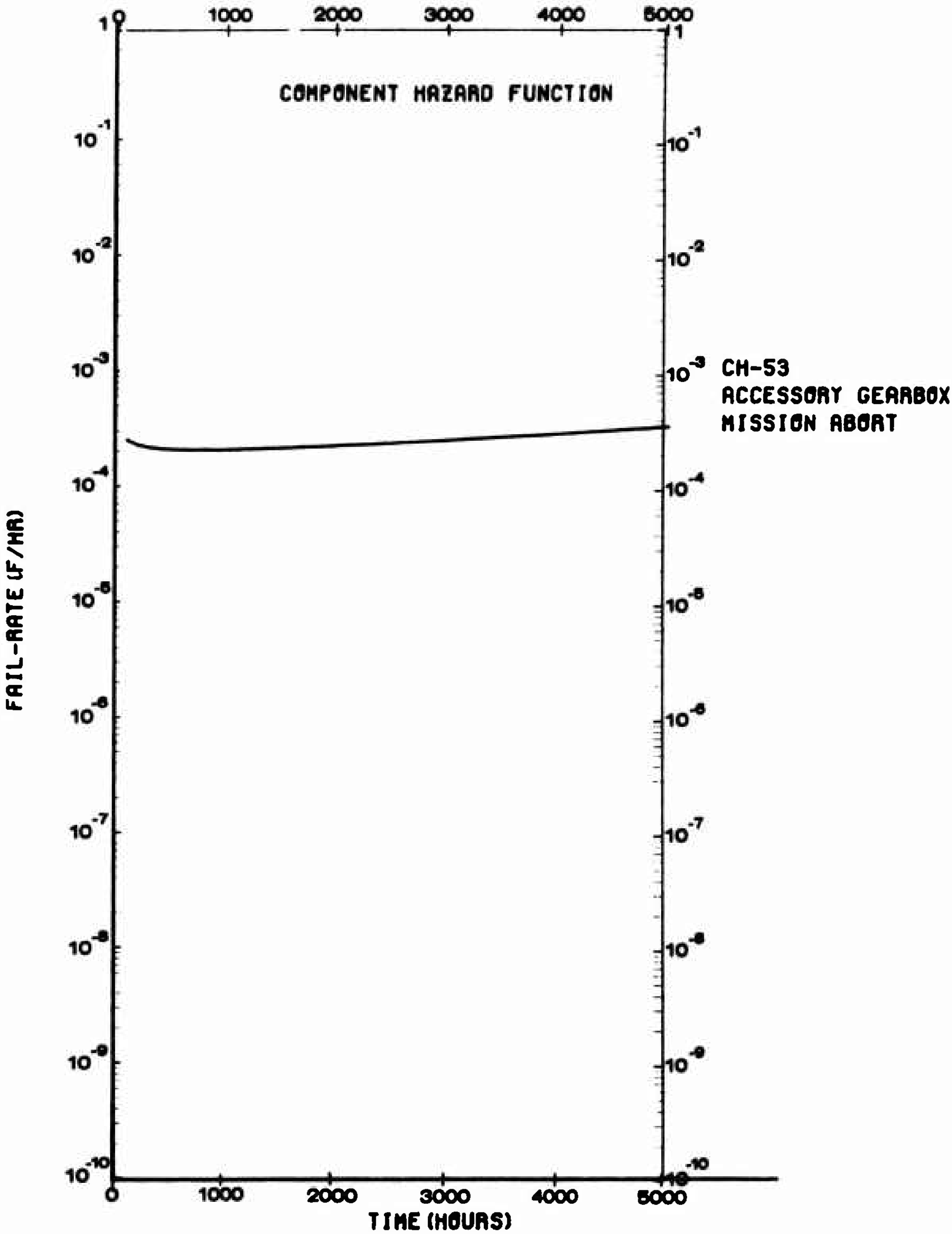

Figure 51. CH-53 Accessory Gearbox Mission Reliability Hazard Function.

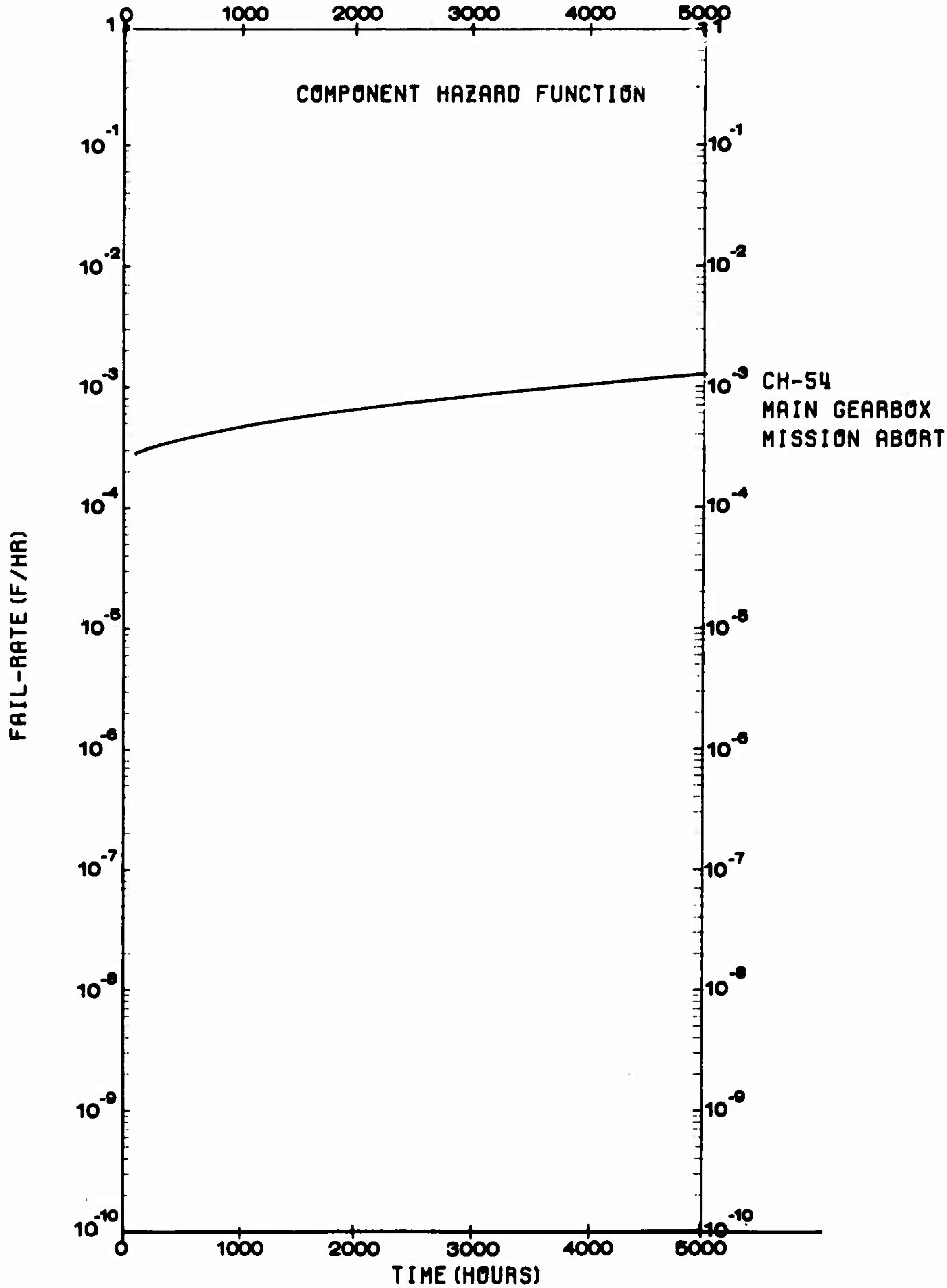

Figure 52. CH-54 Main Gearbox Mission Reliability Hazard Function.

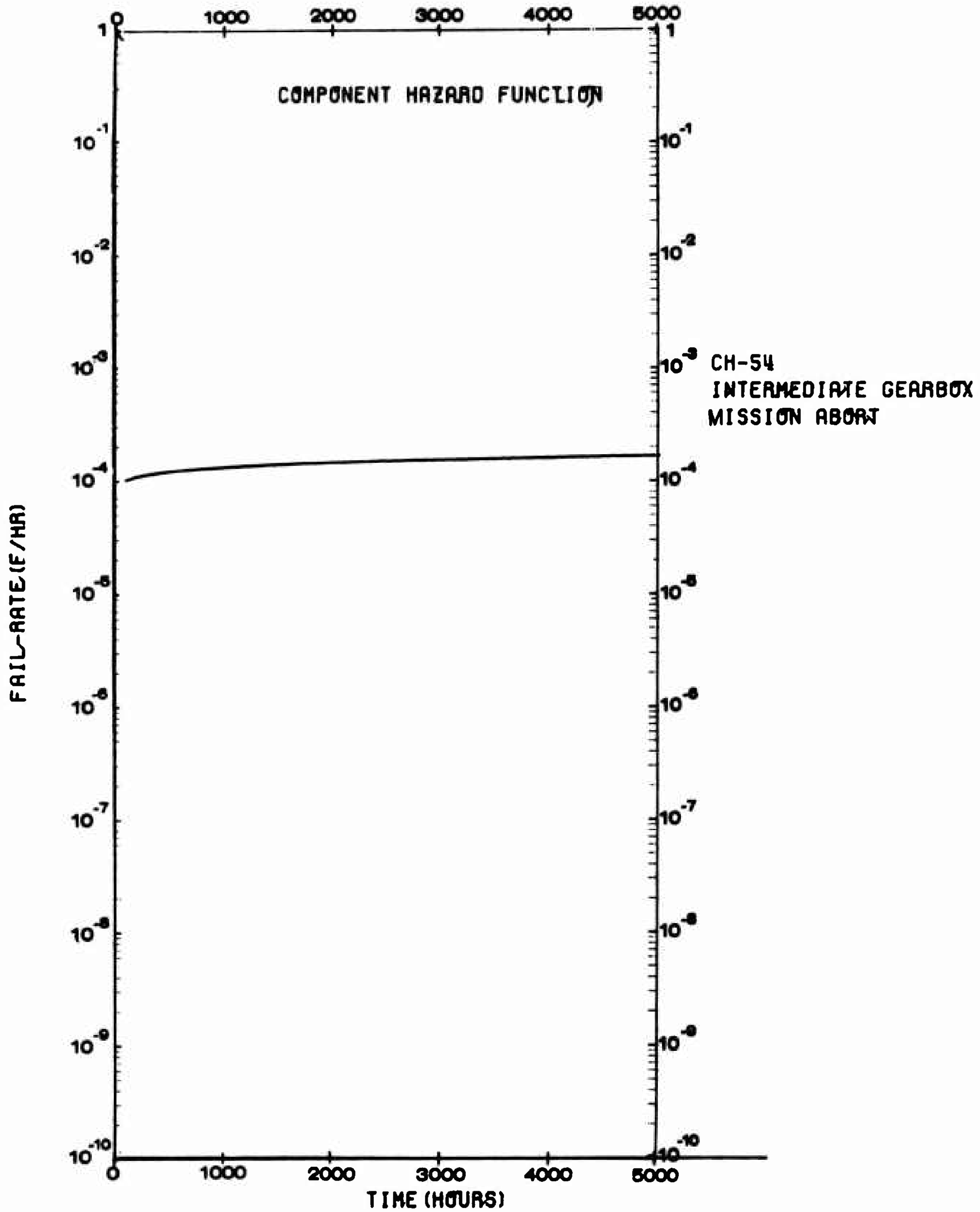

Figure 53. CH-54 Intermediate Gearbox Mission Reliability Hazard Function.

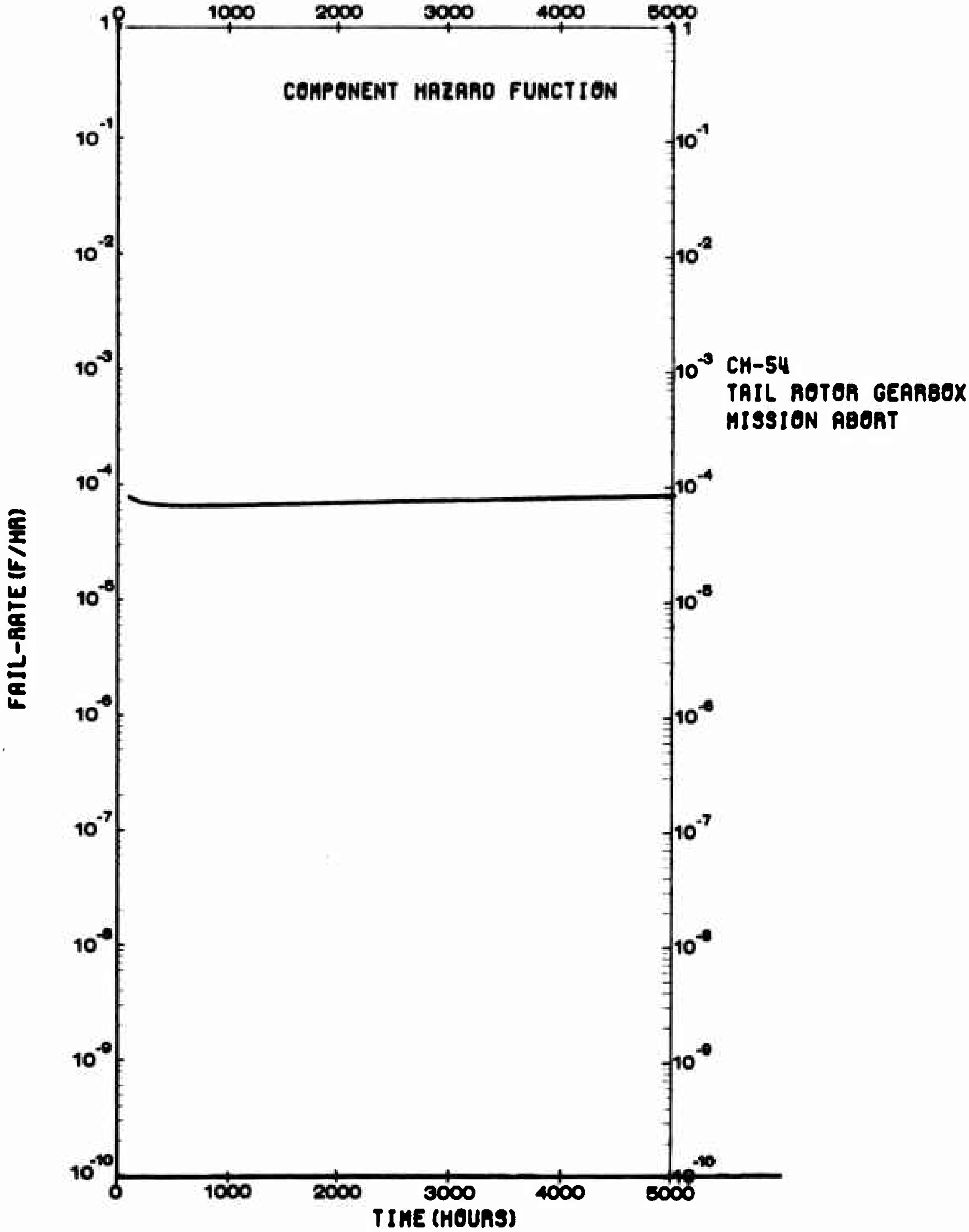

Figure 54. CH-54 Tail Rotor Gearbox Mission Reliability Hazard Function.

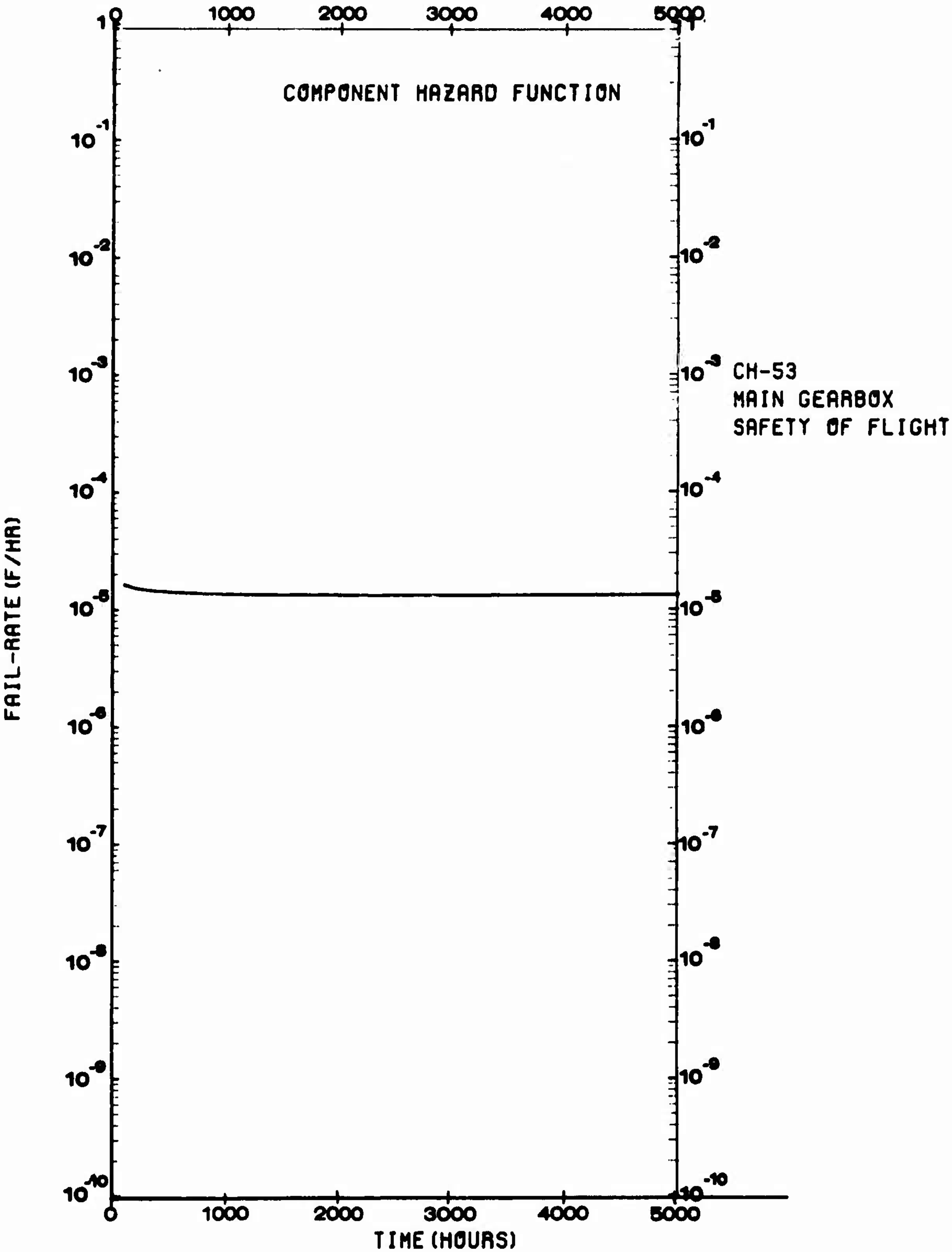

Figure 55. CH-53 Main Gearbox Safety-of-Flight Hazard Function.

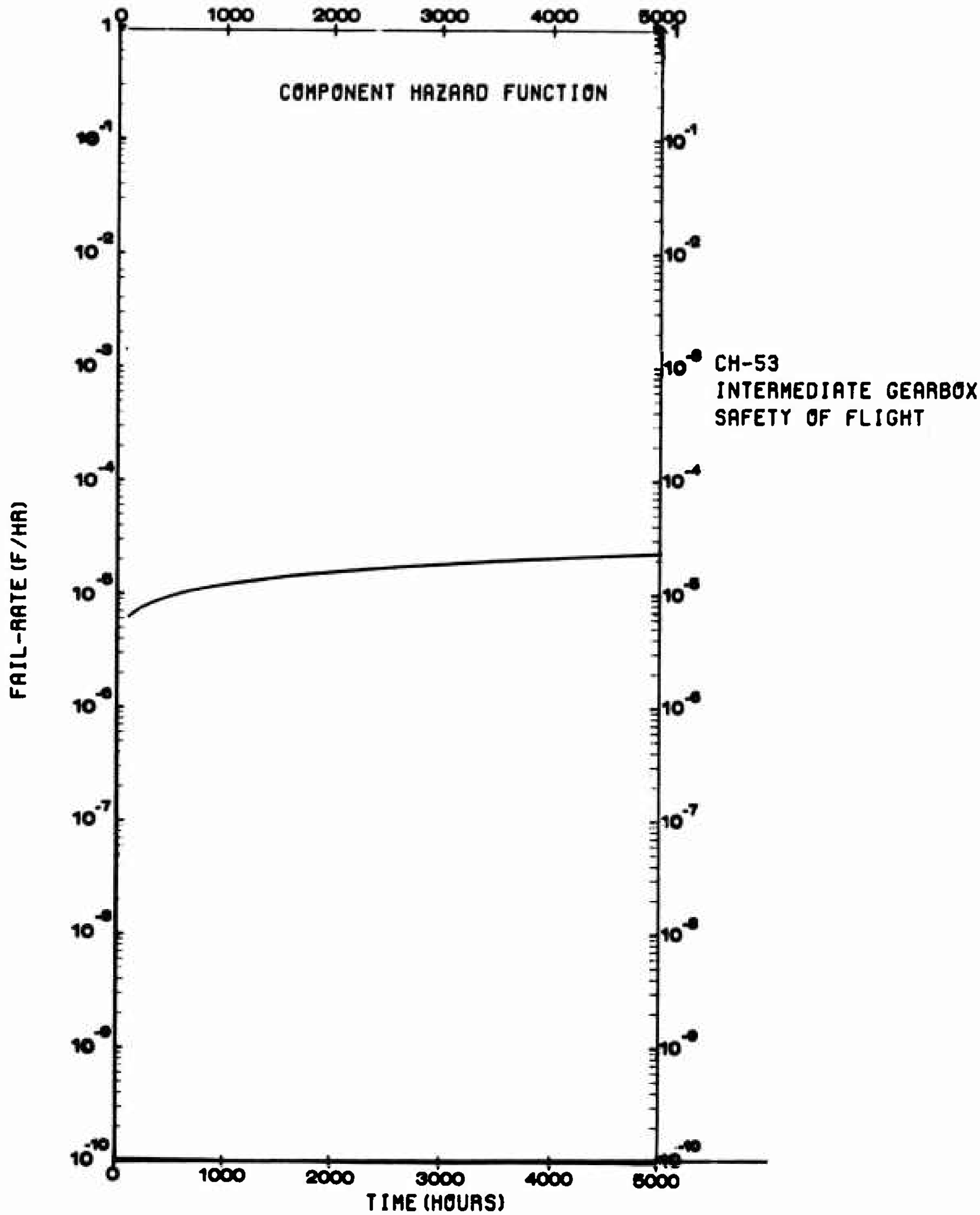

Figure 56. CH-53 Intermediate Gearbox Safety-of-Flight Hazard Function.

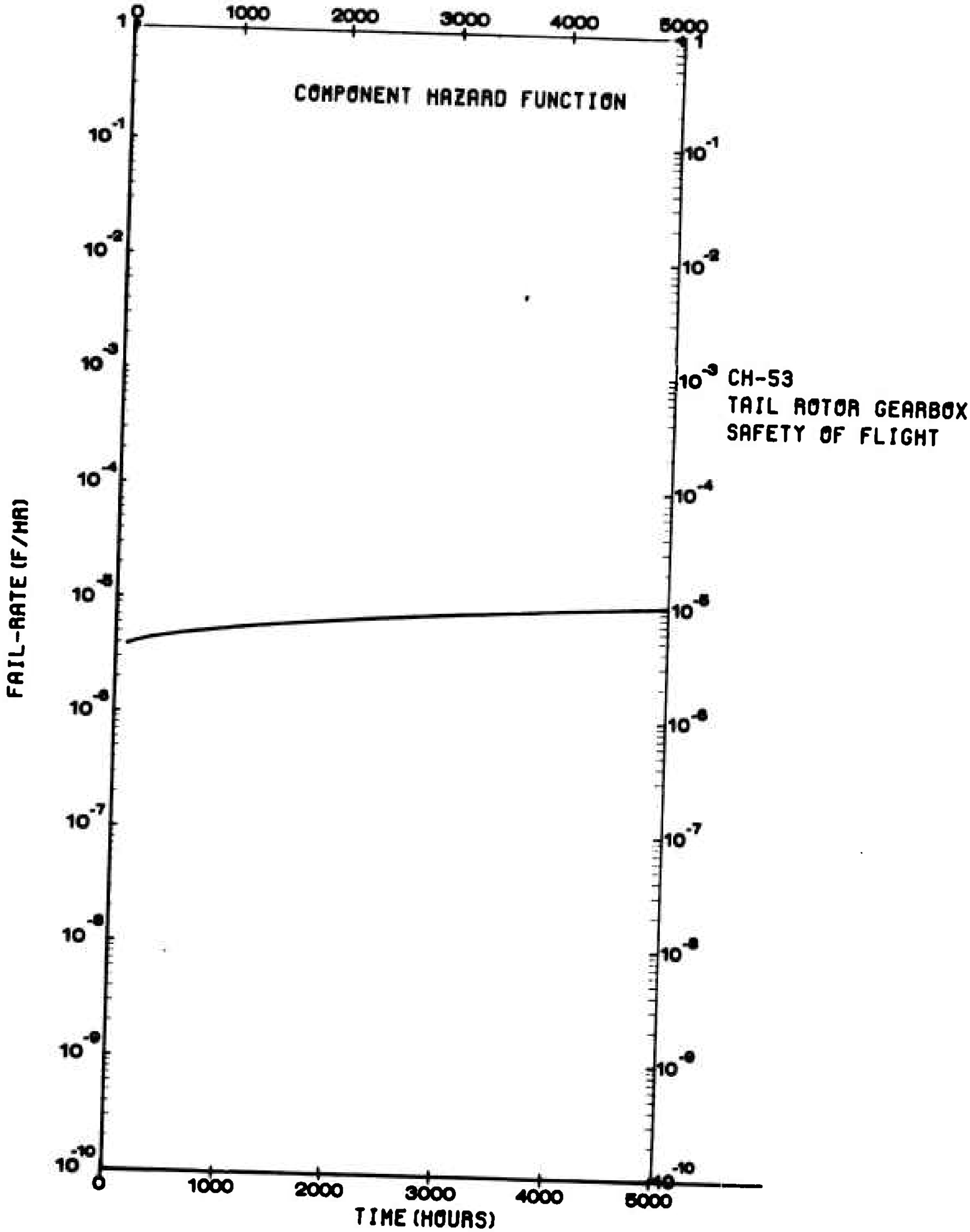

Figure 57. CH-53 Tail Rotor Gearbox Safety-of-Flight Hazard Function.

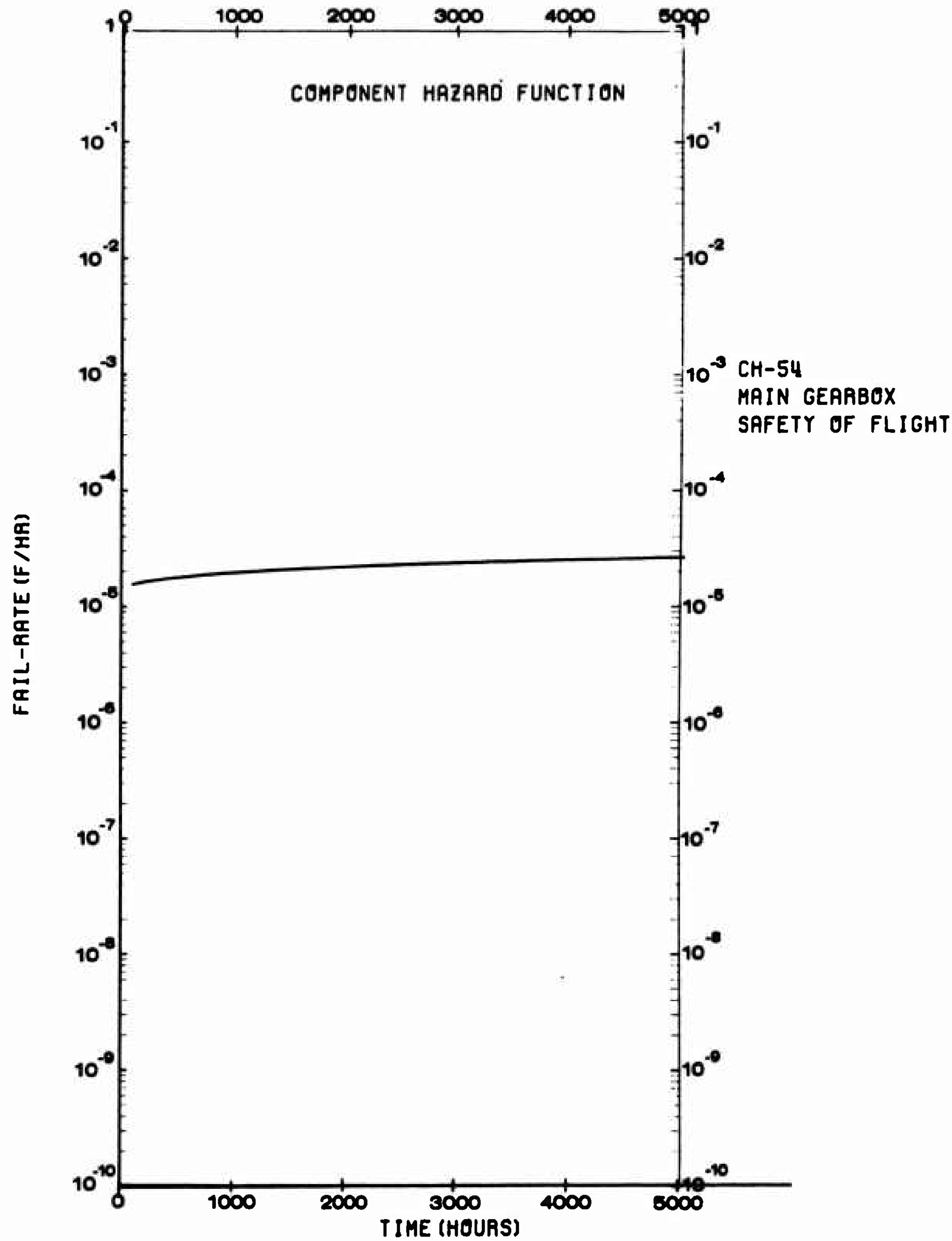

Figure 58. CH-54 Main Gearbox Safety-of-Flight Hazard Function.

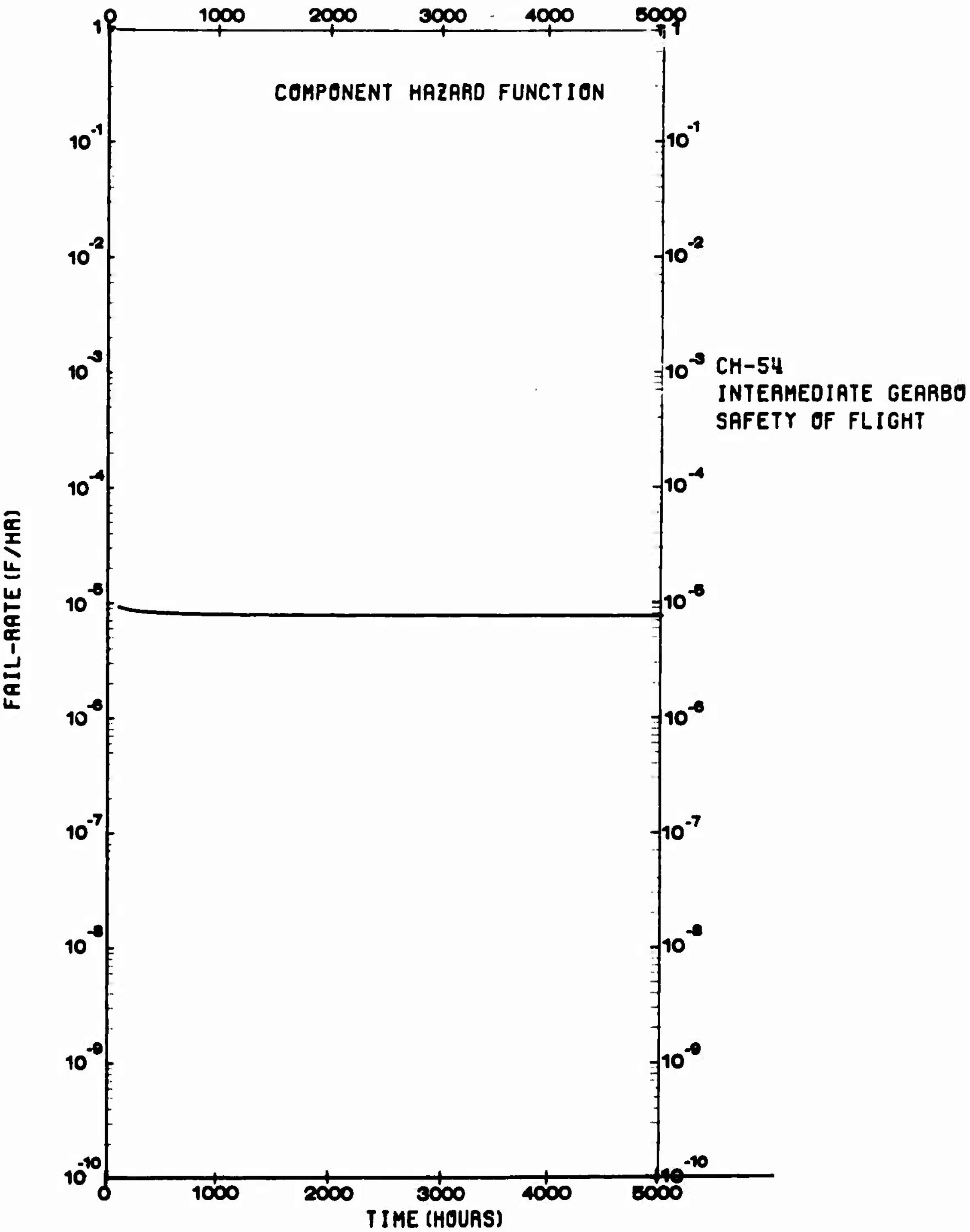

Figure 59. CH-54 Intermediate Gearbox Safety-of-Flight Hazard Function.

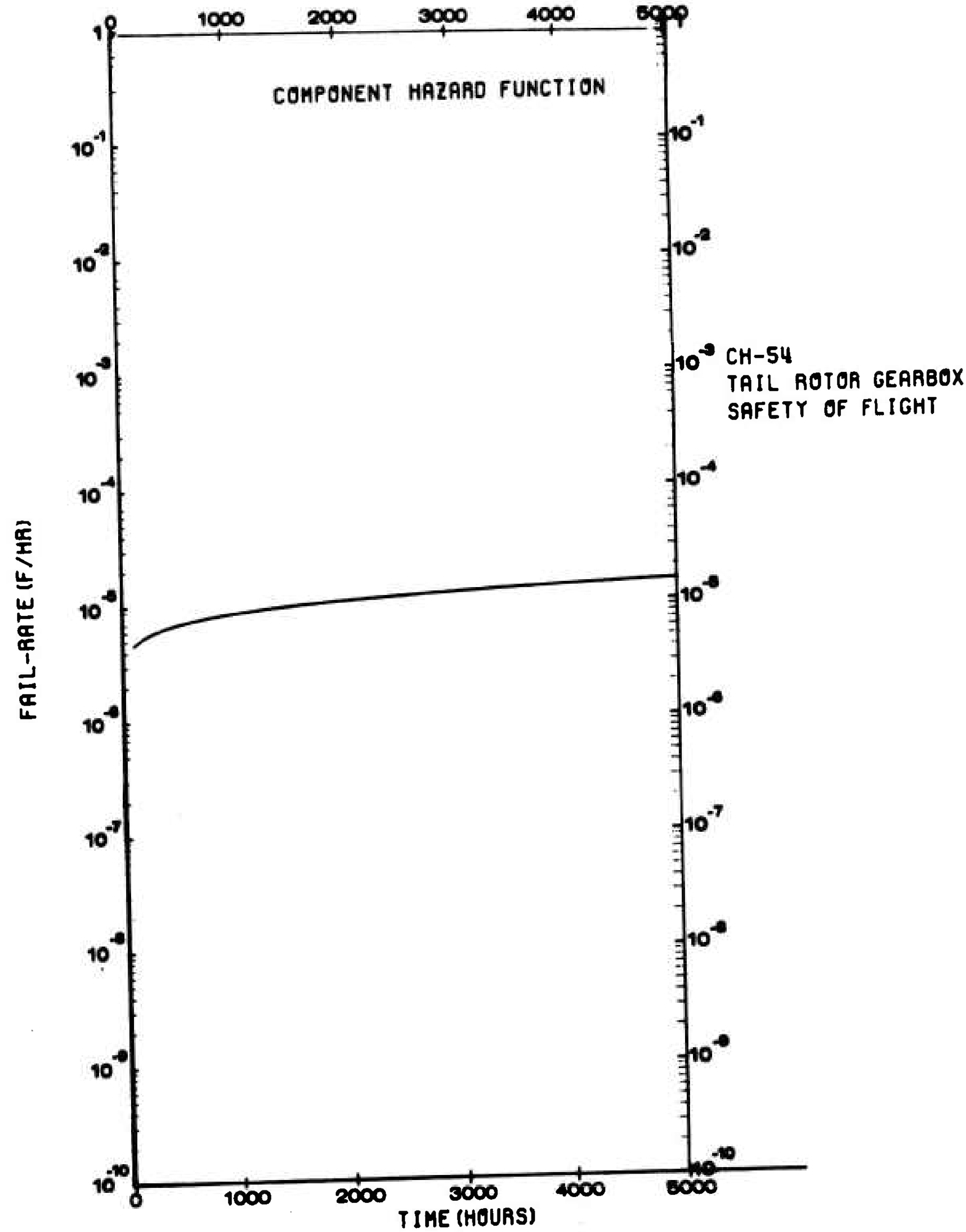

Figure 60. CH-54 Tail Rotor Gearbox Safety-of-Flight Hazard Function.

TABLE 22. SAFETY-OF-FLIGHT HAZARD FUNCTION PARAMETERS

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
CH-54 Main	Spiral Bevel Gear	Tooth Fracture	1.0	$.4886 \times 10^{8}$
		Web/Shaft Fracture	1.0	$.9772 \times 10^{8}$
	Spur Gear	Tooth Fracture	1.0	$.3504 \times 10^{7}$
		Web/Shaft Fracture	1.0	$.3504 \times 10^{7}$
	Spline	Wear, Fretting	1.33	$.3810 \times 10^{5}$
	Ball Bearing	Cage Fracture	1.00	$.1474 \times 10^{6}$
	Roller Bearing	Cage Fracture	1.00	$.6484 \times 10^{7}$
	Tapered Roller Bearing	Cage Fracture	1.00	$.1222 \times 10^{8}$
	Flange	Crack	1.00	$.2453 \times 10^{8}$
	Shaft	Fracture	1.00	$.1546 \times 10^{8}$
	Nuts	Loose	1.70	$.6664 \times 10^{7}$
	Oil Pump	Zero Outlet Pressure	0.63	$.2480 \times 10^{8}$
	Plate Assembly	Fracture	1.00	$.1197 \times 10^{7}$
	Housing	Fracture	2.38	$.2804 \times 10^{6}$
CH-54 Intermediate	Spiral Bevel Gear	Web/Shaft Fracture	1.00	$.2991 \times 10^{6}$
	Roller Bearing	Cage Fracture	1.00	$.2105 \times 10^{8}$
	Tapered Roller Bearing	Cage Fracture	1.00	$.4487 \times 10^{8}$
	Spline	Wear, Fretting	1.50	$.9466 \times 10^{6}$
	Nuts	Loose	1.00	$.1004 \times 10^{7}$
	Clip (Brg) Retainer	Fracture	1.00	$.2770 \times 10^{7}$
	Snap Ring	Fracture	1.00	$.2770 \times 10^{7}$
	Oil Pump	Zero Outlet Pressure	0.63	$.2480 \times 10^{8}$

TABLE 22. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
	Housing	Fracture	1.59	$.1259 \times 10^7$
CH-54 Tail Rotor	Spiral Bevel Gear	Web/Shaft Fracture	1.00	$.8053 \times 10^6$
	Ball Bearing	Cage Fracture	1.00	$.5107 \times 10^8$
	Tapered Roller Bearing	Cage Fracture	1.00	$.7464 \times 10^7$
	Roller Bearing	Cage Fracture	1.00	$.4911 \times 10^7$
	Bearing Retainer	Fracture	1.00	$.4911 \times 10^7$
	Spline	Wear, Fretting	1.50	$.6188 \times 10^5$
	Shaft	Fracture	1.00	$.4911 \times 10^8$
	Nuts	Loose	1.10	$.4162 \times 10^9$
	Housing	Fracture	1.29	$.9142 \times 10^5$
CH-53 Main	Spiral Bevel Gear	Tooth Fracture	1.00	$.1004 \times 10^8$
		Web/Shaft Fracture	1.00	$.3446 \times 10^7$
	Spur Gear	Tooth Fracture	0.71	$.1679 \times 10^7$
		Web/Shaft Fracture	1.00	$.7698 \times 10^8$
	Ball Bearing	Cage Fracture	1.00	$.1346 \times 10^9$
	Roller Bearing	Cage Fracture	1.00	$.3230 \times 10^7$
	Tapered Roller Bearing	Cage Fracture	1.00	$.1673 \times 10^7$
	Spline	Wear, Fretting	1.33	$.2276 \times 10^6$
	Flange	Fracture	1.00	$.5068 \times 10^7$
	Shaft	Fracture	1.00	$.2493 \times 10^6$
	Housing	Fracture	2.38	$.8606 \times 10^5$
	Plate Assembly	Fracture	1.00	$.2442 \times 10^8$
	Oil Pump	Zero Outlet Pressure	0.63	$.2480 \times 10^8$

TABLE 22. (CONTINUED)

Gearbox	Generic Component	Failure Mode	β	θ (Hours)
CH-53 Intermediate	Spiral Bevel Gear	Web/Shaft Fracture	1.00	$.2706 \times 10^{6}$
	Spline	Wear, Fretting	1.50	$.3107 \times 10^{5}$
	Housing	Fracture	1.60	$.1986 \times 10^{7}$
CH-53 Tail Rotor	Spiral Bevel Gear	Fracture	1.00	$.1318 \times 10^{7}$
	Ball Bearing	Cage Fracture	1.00	$.8355 \times 10^{8}$
	Tapered Roller Bearing	Cage Fracture	1.00	$.1671 \times 10^{7}$
	Roller Bearing	Cage Fracture	1.00	$.6106 \times 10^{6}$
	Bearing Retainer	Fracture	1.00	$.8033 \times 10^{7}$
	Spline	Wear, Fretting	1.5	$.8591 \times 10^{5}$
	Shaft	Fracture	1.0	$.8033 \times 10^{7}$
	Nuts	Loose	1.1	$.4967 \times 10^{7}$
	Housing	Fracture	2.19	$.5249 \times 10^{5}$

3.0 IMPLEMENTATION OF ON-CONDITION MAINTENANCE POLICY

An on-condition maintenance policy requires that there be no significant increase in the risk of a safety-of-flight malfunction with the removal of scheduled overhauls. USAAMRDL-TR-73-58 has shown that on-condition maintenance is cost-effective with astronomical increases in the dynamic component removal hazard function with the removal of scheduled overhauls provided there is no significant increase in safety-of-flight malfunctions. While no attempt was made to evaluate life-cycle cost, those design improvements and recommended practices that further enhance on-condition maintenance will be discussed. Their impact on gearbox hazard function will also be shown.

Certain design changes are recommended before an on-condition maintenance policy is initiated, though many are not essential. These improvements are practical and feasible with virtually no increase in the weight of the gearbox. Concurrent with the initiation of an on-condition maintenance policy, it is recommended that field and depot maintenance of on-condition gearboxes be monitored. In the design and development of future gearboxes, it is recommended that the dynamic response of drive system components and the inplane response of gears be evaluated to better direct development testing.

3.1 DESIGN IMPROVEMENTS

Design improvements and procedures that enhance on-condition maintenance for CH-53/54 gearboxes will be discussed in the following paragraphs. At the conclusion of this section, the collective impact of these improvements on existing gearbox hazard function will be presented.

3.1.1 SPLINES

Grease retention is a major design area that warrants improvement for the CH-53/54 gearboxes. The impact of grease retention on spline hazard functions has been previously seen in Section 2.3.3. One improvement that has been incorporated in the improved transmission of the RH-53D helicopter is the addition of a notch and an "O" ring to retain grease in accordance with AS 972A.[13] The "O" ring is essentially a static seal in this application that retains grease in the coupling. A typical installation is shown in Figure 61. While the "O" ring is not viewed as a panacea for spline problems, it is estimated that it will eliminate 85% of the current problems. This is based on the assumption that spline couplings are not misaligned and that shaft speed, by centrifugal force, does not keep the lubricant from mating surfaces.

While grease retention is not a problem with critical splines, the possibility of fretting wear would be further reduced by the above improvement. In this sense, the above improvement is considered to be essential for implementing an on-condition maintenance policy.

To further reduce the possibility of spline wear and fretting, difficulties

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[13] AS 972A, "Spline Details, Accessory Drives And Flanges", Aerospace Standard, October 13, 1967.

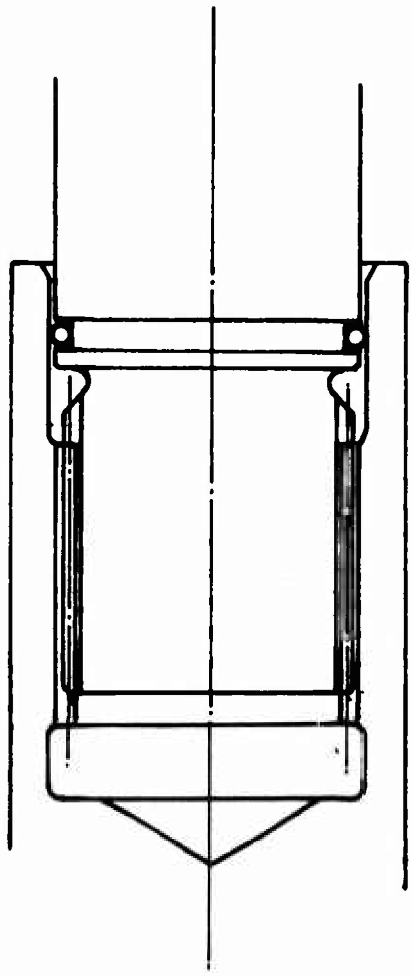

Figure 61. Grease Lubricated Spline
Lubrication Retention Improvement.

inherent to the manufacture and application of involute splines must be addressed. These include eccentricities between shafts, minor distortions of spline teeth after heat treatment, backlash of the coupling, and inherent surface roughness that results after machining, especially in making small accessory splines.

Fortuna-Werke Maschinenfabrik A. G., a leading West German manufacturer of production cylindrical grinding machines, has recently developed a machine that can accurately grind internal and external shapes like those shown in Figure 62. This system is known as the polygon system and depends on a manufacturing process called polygon grinding.

Polygon splines can be used as direct replacements for involute splines in helicopter transmissions, as shown in Figure 63. The polygon spline can be tapered to serve the dual functions of transmitting torque and head moment when used as a rotor head connection. Because the shear length of the polygon spline is longer than that of the involute spline, a polygon spline is stronger in shear.

These splines are ground continuously and extremely accurately. The ground profiles are perfectly symmetrical, concentric to shaft center, and repeatable in manufacture to within millionths of an inch. This degree of accuracy eliminates the possibility of unequal load sharing of the lobes due to machining errors.

The polygon system can yield a connection with the following advantages over conventional splines:

- Higher angular shear strength
- Higher torsional shear strength
- Lower backlash
- Self-centering (elimination of pilot diameters)
- High accuracy of angular orientation
- Parts finished after heat treatment
- Ease of manufacture
- Lower cost

In a helicopter transmission, the polygon spline connection offers the added advantage of eliminating the stress risers associated with conventional splines. The most attractive application of the polygon spline is the connection of main rotor shaft to main rotor head. This connection is usually made with involute splines to transmit torque and with auxiliary devices to transmit rotor thrust and moments to the shaft. These auxiliary devices are solid or split cone-shaped members that are forced between the main rotor shaft journals and the rotor head with preloading devices. This results in a complex system with many parts. The journals on the shaft or hub become fretted, causing scrappage of expensive components.

While the polygon spline is not essential to implementing an on-condition maintenance policy, its advantages certainly warrant its further consideration in future transmission development.

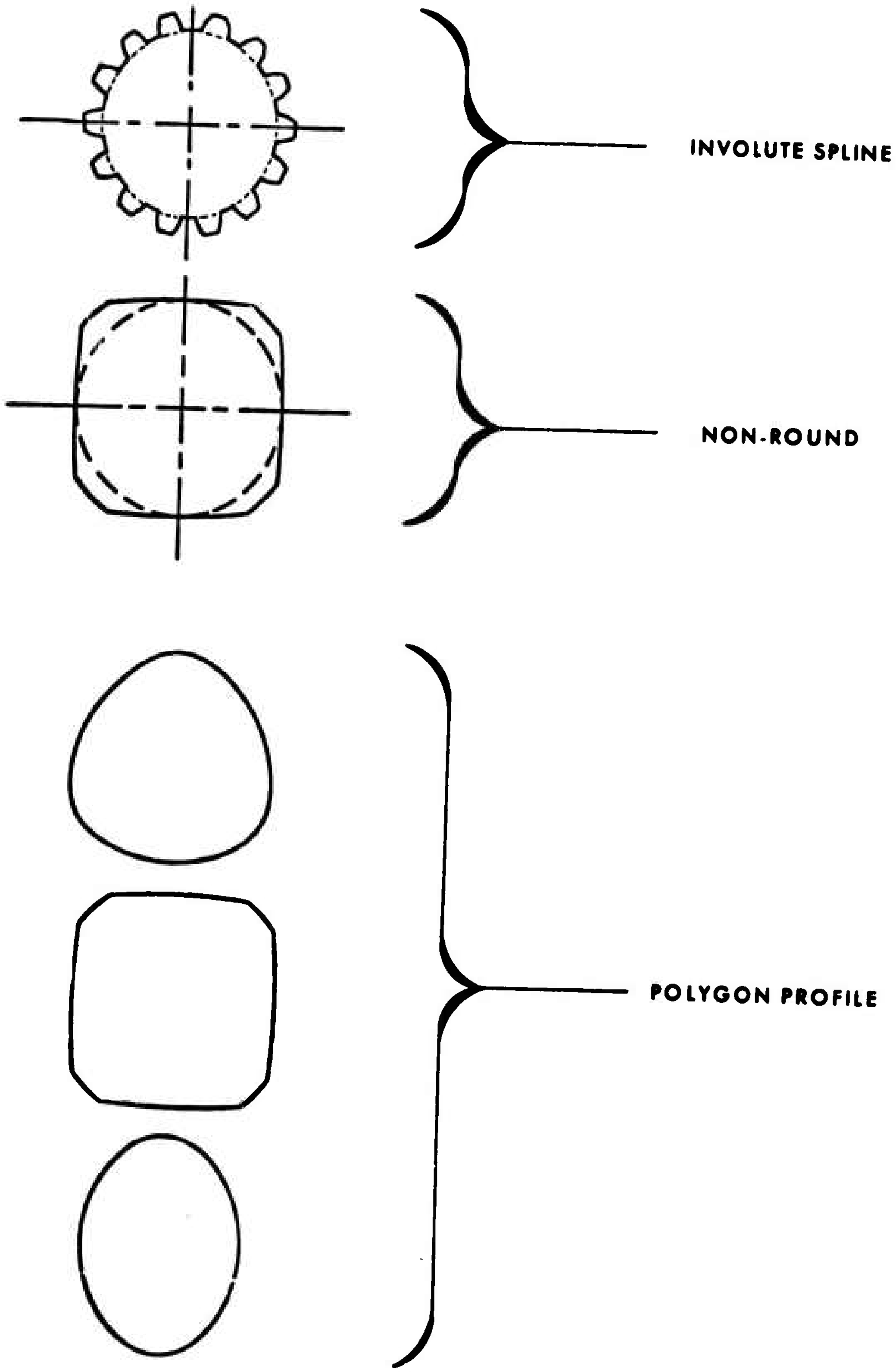

Figure 62. Polygon Spline Shapes.

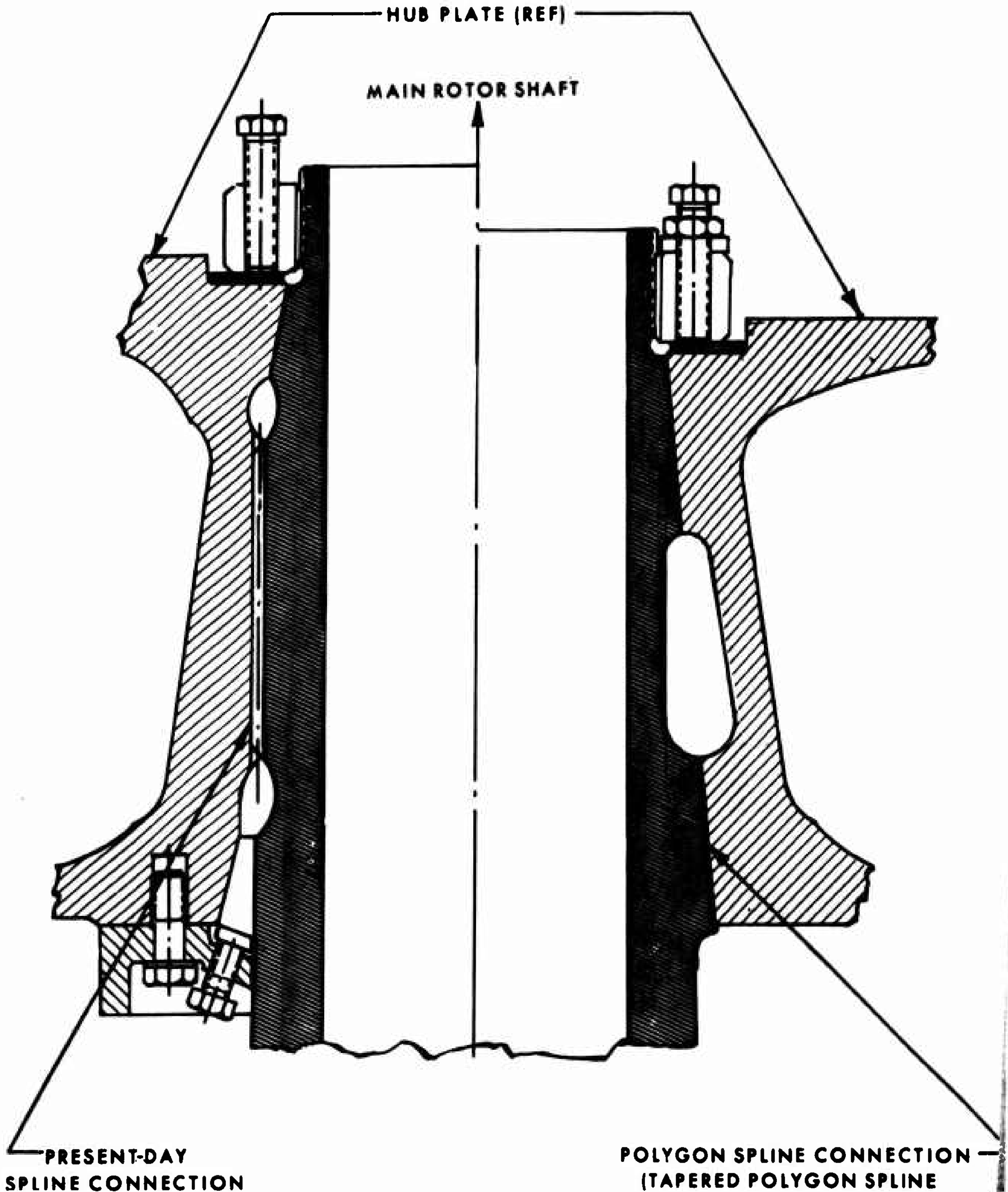

Figure 63. Polygon Spline Shaft Replacement.

3.1.2 HOUSINGS

Cracks in the mounting lugs of tail rotor gearboxes and bolt holes of intermediate gearboxes indicate that improvement is warranted. Improvements that will be briefly discussed have been incorporated in later versions of the gearboxes that were studied.

On the RH-53D, the problem of tail rotor gearbox mounting lug cracks was addressed by reducing the stress concentration in the mounting lugs and changing the housing material to permit better control of the core hardness. Stress concentrations were reduced by making lugs thicker and with larger radii of curvature. The improved consistency of core hardness results from better control of the pouring process in forming gearbox housings offered by magnesium alloy ZE41 over magnesium alloy AZ91. The impact of this improvement on gearbox weight is only a 1-pound increase.

On the CH-54, the problem of bolt-hole cracks of the intermediate gearbox were addressed by reducing the stresses in each load path of the mounting flange. This was done by doubling the number of bolt-holes (load paths) while maintaining their original strength. With this improvement, intermediate gearboxes on the CH-54A's were placed on-condition.

While the above improvements do not impact all housing failure modes, such as corrosion, it is felt that they can significantly reduce the possibility of housing cracks. Even though housing cracks have never caused a safety-of-flight malfunction of the CH-53/54, the above improvements are considered to be essential to implementing an on-condition maintenance policy to further reduce this possibility.

Inspections are adequate to detect any housing cracks that result from corrosion. As a result, with the above improvements and existing inspections (see Section 2.2), the possibility of a housing fracture is remote.

3.1.3 FREEWHEEL UNITS

The significance of freewheel unit roller malfunctions on the CH-54 dynamic component removal and mission reliability hazard functions (see Tables 17 and 19) indicates that improvements are desirable. Minimal lubrication is in part responsible for these malfunctions. Two improvements, one specifically aimed at the failure modes of the CH-54 and another aimed at improving the reliability of the conventional freewheel unit, will be briefly discussed.

PRESSURIZED LUBRICATION SYSTEM

In a conventional freewheel unit lubrication system, oil is fed to the center freewheel member whereupon it is metered to the rubbing clutch components (such as the rollers of a ramp roller clutch). If the innermost member of the freewheel unit is the driving member, it will be stopped during overrunning. Thus the oil is fed only by gravity to the lower components and does not have centrifugal force acting to assist lubrication at the time when lubrication of the freewheel unit is important; that is, overrunning.

If the feed jet to the freewheel unit is sealed so as to form a chamber on the innermost freewheel unit shaft, the shaft will fill with oil and force it to all the freewheel unit overrunning components. Thus, proper lubrication is assured during overrunning.

SPRING CLUTCH

The principle of operation of the spring clutch is depicted schematically in Figure 64. A spring of rectangular cross section is positioned between two concentric internal shaft diameters. The end coils of the spring are of a larger diameter than the central coils and are in contact with the bores of the shafts. When the two shafts are twisted relative to each other so as to tighten the spring, the end coils slip on the shaft bores. When the two shafts are twisted so as to unwind the spring, the spring expands and grips the shaft bores along its entire length. In this position the spring is able to transmit torque from one shaft across the gap to the other shaft.

The center coil of the spring which bridges the gap between shafts must transmit the full torque through the spring coil cross section. The load along the length of the spring then gradually decreases as the torque is transmitted into the housing.

The least expensive method of manufacture of the spring is a coil of constant section wire, heat treated and finished machined. Since the center section must carry the full torque, and the wire is of constant section, the end coils have very low stress. With this design, however, the spring is excessively long. A constant stress spring is the lightest solution. In a constant stress spring clutch, the thickness of the spring will vary parabolically with length.

The typical spring overrunning clutch is shown in cross section in Figure 65. Note that in this design the spring thickness in both the axial and radial dimensions is varied to obtain an approximation of a parabolic constant stress function. The central coils of the spring are relieved. During overrunning, the spring contacts only on the end coils, which are designed with an interference fit. The spring guide arbor holds the spring in alignment during overrunning and forces the slippage to occur on the end coils of the shaft opposite the shaft attached to the arbor.

The clutch outer housing member has two bearings which support the clutch outer shaft independently of the input shaft. Relative rotation between input and output clutch shafts is permitted by the preloaded tandem bearings between the two members. Bearing brinelling is minimized with this bearing arrangement.

Lubricant is fed through either end of the clutch to the inner shaft member, where it will feed past the slotted end spacer, over the end coils of the spring which are also slotted, and through the drain holes in the input shaft bore. During overrunning, the oil must pass over the only portion

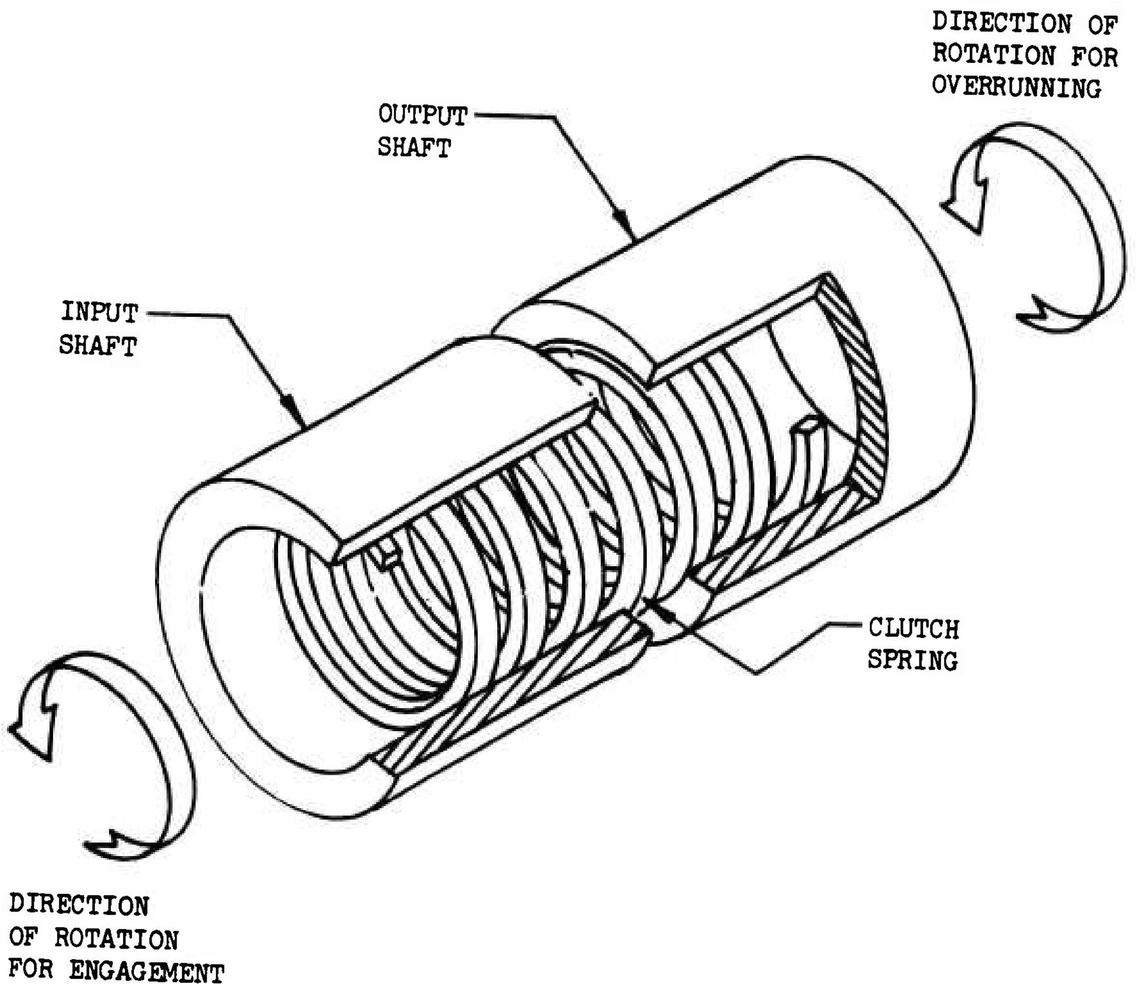

Figure 64. Principle of Operation, Spring Overrunning Clutch.

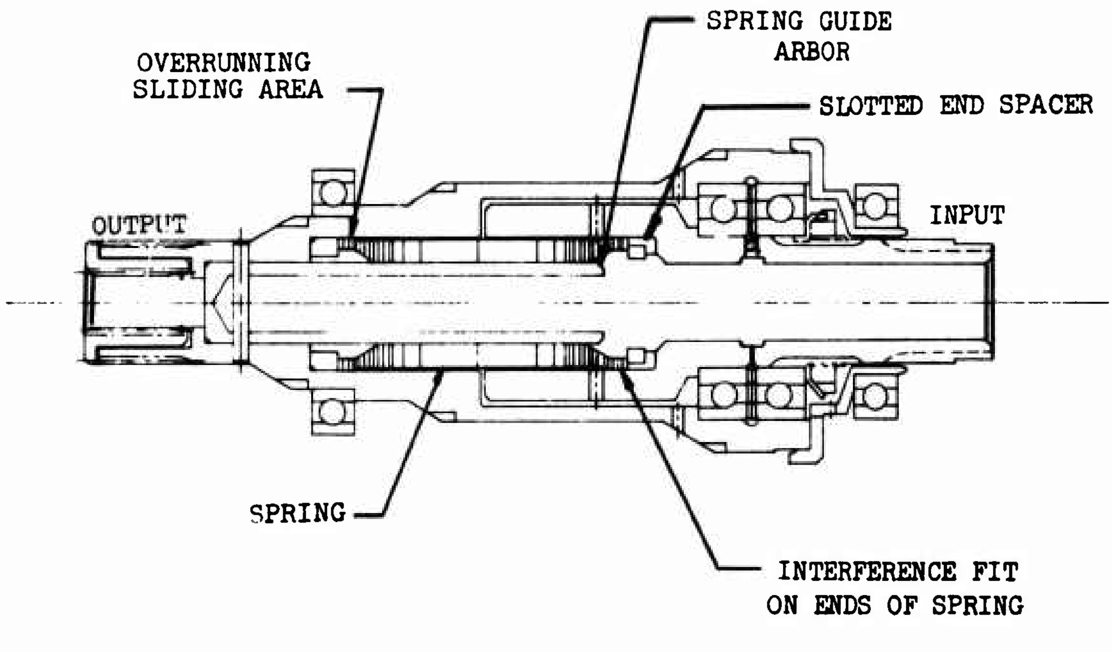

Figure 65. Spring Overrunning Clutch.

of the spring which is rubbing, thereby assuring proper lubricant flow to the area required. The duplex bearings are also lubricated through central holes in the input shaft and through slots at the bearing interfaces. The outer support bearings are lubricated by fixed jets in the support housing.

Assuming proper lubrication, especially during overrunning, the spring clutch offers a reliability improvement over the conventional freewheel unit. The possibility of pitting or flaking is virtually eliminated since there are no high contact stresses, assuming the spring has a constant stress concentration. A cage fracture is impossible. Wear of rubbing surfaces is the only failure mode common to the conventional freewheel unit. With adequate lubrication, the frequency of wear failures of the spring clutch is anticipated to be at least comparable to the conventionals.

3.1.4 BEARINGS

Failure modes attributed to minimal lubrication are the only bearing failure modes which significantly affect gearbox hazard functions. The two areas encountered in this study, CH-53 main gearbox planetary roller bearings and CH-53 intermediate gearbox tapered roller bearings, require different design solutions.

Planetary roller bearings represent a difficult application for lubrication. Oil is distributed to each bearing with the aid of centrifugal force from a collector ring on the planet carrier. However, due to the relatively slow rotational speeds of the planetary assemblies, only minimal lubrication can be provided. This causes the bearings, as noted in Section 2.3.1, to operate at a higher temperature than is generally recommended for AISI 52100 steel bearings.

Planetary roller bearings appear to be an ideal application for M-50 CVEM bearings. M-50's ability to retain its hardness at much higher temperatures makes it suitable for this application. At normal operating temperatures, 180°F to 200°F, M-50's hardness and 52100's hardness are comparable, so normally there is little advantage in using M-50 bearings in lieu of 52100 bearings. Alternative pressure lubrication schemes to the current one appear at best more complex.

On the other hand, the CH-53 intermediate gearbox's input tapered roller bearings do provide an opportunity for a type of pressurized lubrication. Originally oil was fed to both tapered roller bearings that support the input bevel gear from a common port in the gearbox housing (see Figure 14). This discussion pertains to gearboxes without the oil dam. However, most of the oil went to the main supporting bearing and resulted in a number of lubrication-caused malfunctions of the preload bearing. A simple pressurized lubrication system is made by placing an oil dam between the port and the main support bearing. This forces oil past the preload bearing, into another port, and finally past the main support bearing. The RH-53D helicopter has incorporated this pressurized system in its improved transmission at virtually no increase in weight.

The recommendations above are expected to reduce the significance of the associated hazard functions and to change their shape. Shape parameters are expected to be reduced to about 1.3 for spalling failure modes and the overall magnitude reduced by 93%. While the above improvements are not essential for implementing on-condition maintenance, they are desirable for improving product reliability.

3.1.5 PITCH CHANGE CONTROL ROD ANTIROTATION GROOVE

Improvements of the antirotation groove are aimed at reducing the wear rate between rubbing surfaces. Two different schemes are described.

The first method, shown schematically in Figure 66, employs a roll pin to allow linear motion of the pitch change control rod. The idea behind this method is to substitute rolling friction for sliding friction and thereby reduce the actual wear rate. The difficulties in applying this concept are that the same materials are involved, titanium and steel, and the possibility of higher contact stresses. Higher stresses result from a line contact being substituted for an area contact. The only way around this is to use more pins to reduce the stresses transmitted by each pin. Furthermore, bearing failure modes of the roll pin assembly reduce the attractiveness of this concept.

The second approach would maintain the current groove and would pressure plate a thin strip of stainless steel to each side of the groove. The idea here is to use a harder material to reduce the wear of the slot. Of course, wear of the shaft key is bound to increase. Nevertheless, the wear of the coupling should be reduced.

The second approach should be able to reduce fretting of the antirotation groove. The first approach would require a detail design before an assessment would be possible. In any event, while improvement is desired, it is not essential to implementing an on-condition maintenance policy.

3.1.6 CLIPS, BEARING RETAINERS, AND LOCKING ASSEMBLIES

Improvements to clips, bearing retainers, and locking assemblies are primarily aimed at making them more tolerant of their environments. While many improvements to these items were made as a result of the improved RH-53D transmission design, only the two most significant will be described. The remainder will be summarized in the next section.

Improvements to locking assemblies apply to those which employ a serrated lock washer when internal shaft vibration causes shaft serrations to wear. Examples of these are the input retention nut of the CH-53 nose gearbox and CH-53 accessory gearbox retention nuts. The major improvement is to employ a jam nut. The idea is to reduce the stress levels by distributing the vibratory loads over the length of several threads rather than just the serrations. As with the lock washer, the jam nut's movement is synchronized to the retention nut's by tangs. It is anticipated that the reduced stresses and wear should significantly reduce the shape parameter (from approximately 1.7 to about 1.1) as well as the overall frequency for this mode.

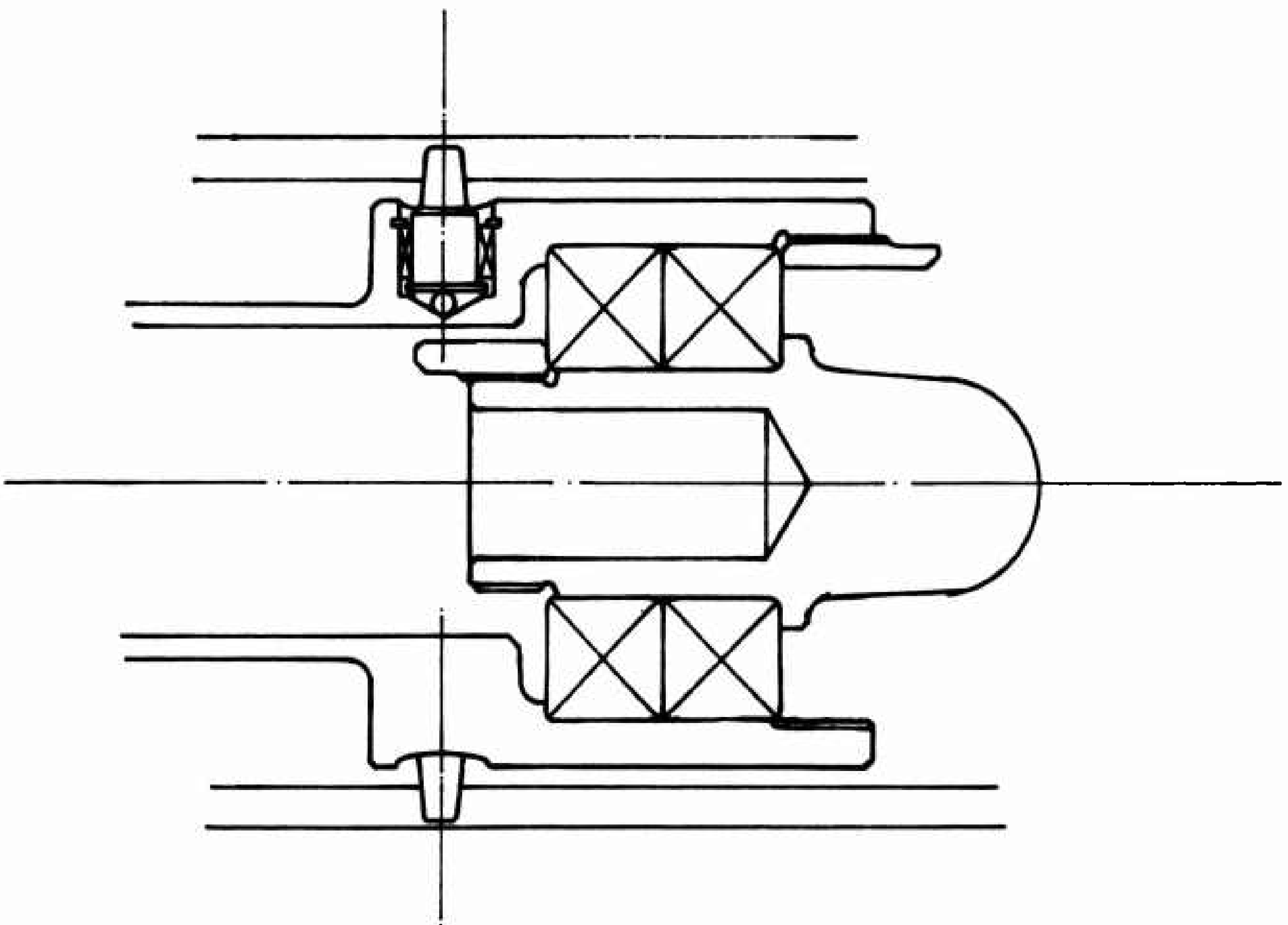

Figure 66. Pitch Change Control Rod Antirotation Groove Improvement.

Sun gear clip improvements (see Section 2.3.9) reduce the wear rate by doubling the number of clips and increasing the area of each clip. This not only reduces the stresses involved but also increases the amount of material that has to wear away before failure can occur. As a result of these improvements, the shape parameter and the overall frequency of occurrence for sun gear clip wear failures are also expected to decrease.

3.1.7 IMPROVEMENT IMPACT

The effect of component improvements on generic mode hazard functions was assessed by engineering judgement. Each improvement's impact was evaluated in terms of the number of failures that might have been prevented. This in turn was converted to a percentage improvement and the new hazard function parameters calculated by the techniques of Appendix A, Section A.1.2.2.5. If an improvement significantly reduced the factors influencing the shape parameter, such as wear rate, the shape parameter was reduced based upon a comparison with other similar installations.

Listed in Table 23 are the items responsible for improving generic mode hazard function parameters. Figure 67 through 88 shows their benefit to component hazard functions. The figures indicate that there would be no significant increase in potential safety-of-flight malfunctions, and that mission reliability failures and dynamic component removal failures would be at levels which permit effective operation if on-condition maintenance were implemented.

3.2 LIFE-LIMITED COMPONENTS

Life-limited components of the CH-53/54 gearboxes do not diminish the feasibility of on-condition maintenance. The term life limited describes just those components with definite retirement times rather than those with increasing hazard functions. There are no life-limited drive components in the CH-53 gearboxes. The only component that was life-limited was the pitch change control shaft of the tail rotor gearbox. This flight control component has been redesigned in the latest version of the gearbox to remove the life-limitation. The CH-54A has two life-limited components: the main rotor thrust bearings and the main rotor shaft. The main rotor thrust bearings were redesigned for the CH-54B and the life-limitation was removed. The main rotor shaft is a design that is over ten years old. With the knowledge that has been gained over the years about shaft failure mechanisms, no problem is anticipated in designing a shaft with an infinite life. The fact that the CH-53 shaft has an infinite life reinforces this contention.

3.3 DATA COLLECTION

Every sign in this study points to the feasibility of an on-condition maintenance policy for the CH-53/54 transmission. Yet this conclusion must be verified by actual field experience. As a result, it is recommended that field and depot maintenance of on-condition gearboxes be monitored. Such a program is desirable to verify projection of the hazard functions as well as to keep abreast of any problem areas.

TABLE 23. RECOMMENDED IMPROVEMENTS TO CH-53/54 GEARBOXES

Aircraft	Gearbox	Generic Component	Improvement
CH-54	Main	Spline	. Add "O" ring to grease lubricated splines.
		Freewheel Unit Rollers	. Incorporate pressurized lubrication into free-wheel unit to insure proper lubrication during overrunning.
	Inter-mediate	Housing	. Double number of bolts while maintaining their original strength.
		Spline [a]	. Add "O" ring to grease lubricated splines.
	Tail Rotor	Housing	. Increase strength of mounting lugs and change material to magnesium alloy ZE-41.
		Spline [a]	. Add "O" ring to grease lubricated splines.
		Pitch Change Control Rod Antirotation Groove	. Add stainless steel insert to existing groove.
CH-53	Main	Bolts	. Stainless steel bolts in lieu of titanium bolts for planetary assemblies.
		Sun Gear Clips	. Additional clips of increased area.
		Roller Bearings	. Use of M-50 bearing for planetary roller bearings.
		Bearing Retainer	. Improved bearing retainer in the left-hand input accessory takeoff section to provide increased protection against bearing outer race rotation.

[a] Incorporation of "O" rings to the grease lubricated splines in these gearboxes is considered to be essential to further reduce the possibility of critical spline failure.

TABLE 23. (CONTINUED)

Aircraft	Gearbox	Generic Component	Improvement
CH-53		Spline [a]	. Add "O" ring to grease lubricated splines.
	Inter-mediate	Tapered Roller Bearings	. Pressurized lubrication system.
		Spline [a]	. Add "O" ring to grease lubricated splines.
	Tail Rotor	Housing	. Increase strength of mounting lugs and change material to magnesium alloy ZE-41.
		Spline [a]	. Add "O" ring to grease lubricated splines.
		Pitch Change Control Rod Antirotation Groove	. Add stainless steel insert to existing groove.
	Nose	Tachometer Generator Spur Gear	. Optimize tooth profile geometry to reduce sliding and improve lubrication.
		Nuts	. Incorporate jam nuts in lieu of serrated lockwashers.
		Bearing Retainer	. Incorporate a new one-piece retainer to provide improved bearing retention.
	Access-	Splines	. Add "O" ring to grease lubricated splines
		Nuts	. Incorporate jam nuts in lieu of serrated lockwashers.

[a] Incorporation of "O" rings to the grease lubricated splines in these gearboxes is considered to be essential to further reduce the possibility of critical spline failure.

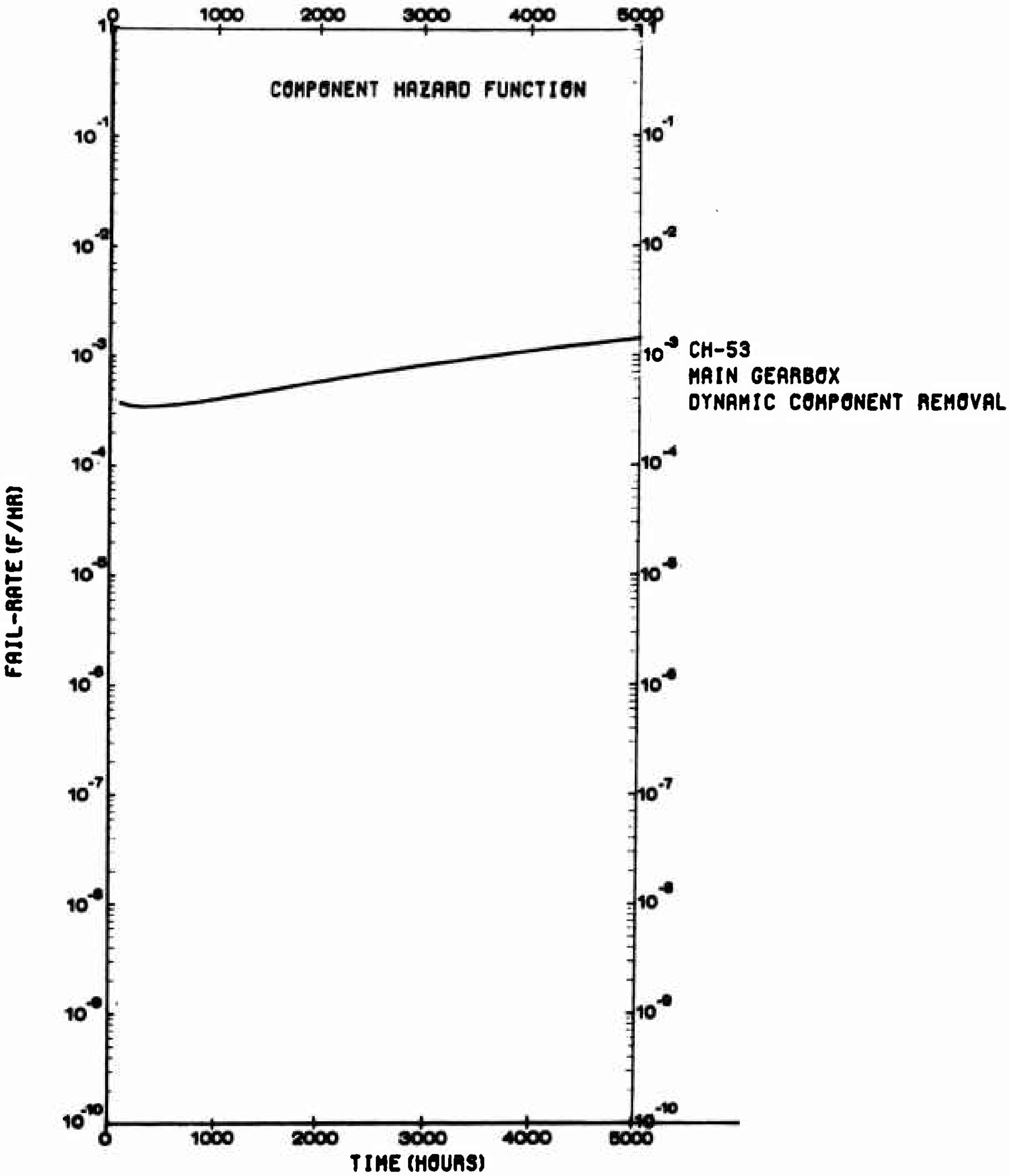

Figure 67. Improved CH-53 Main Gearbox Dynamic Component Removal Hazard Function.

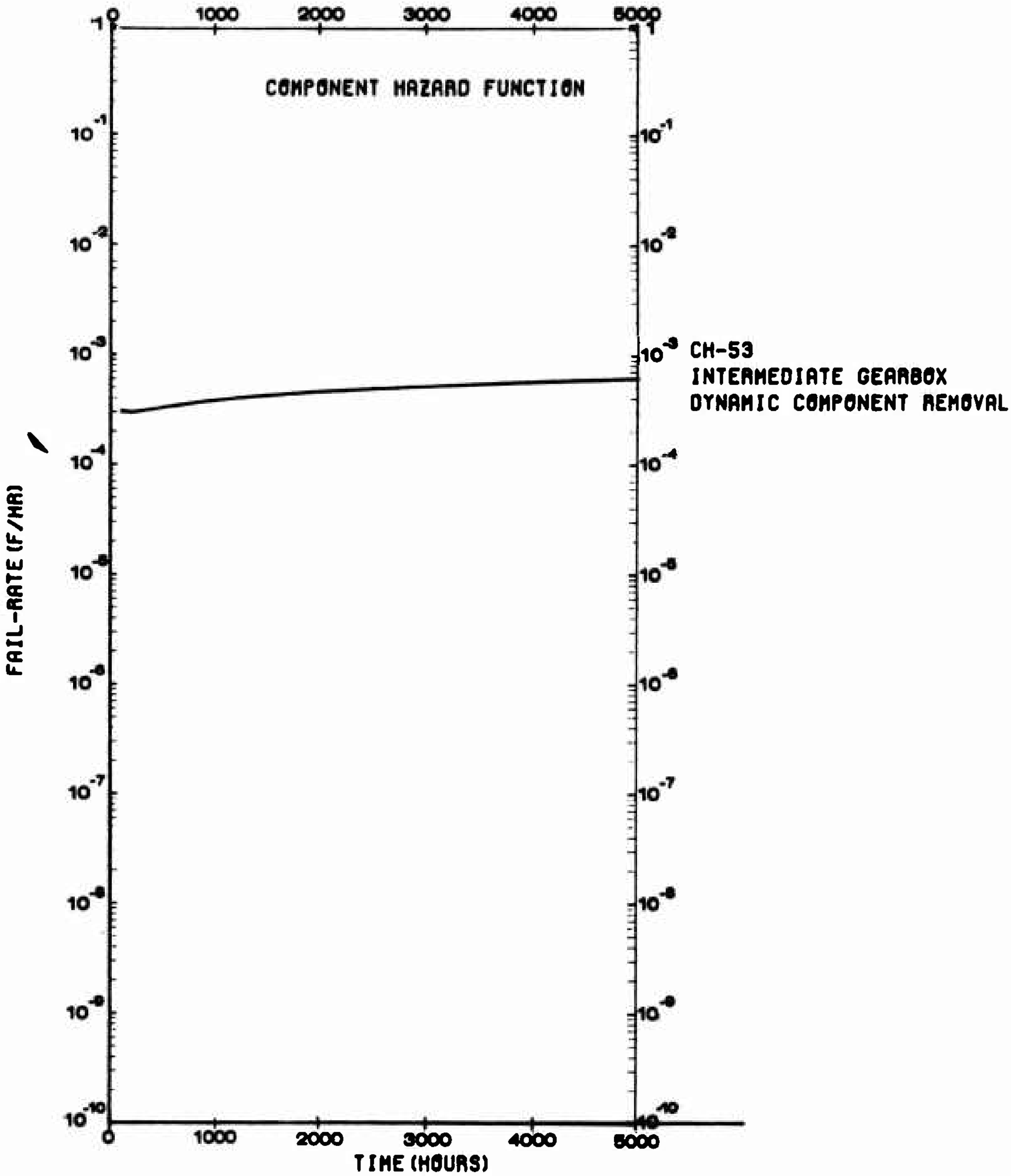

Figure 68. Improved CH-53 Intermediate Gearbox Dynamic Component Removal Hazard Function.

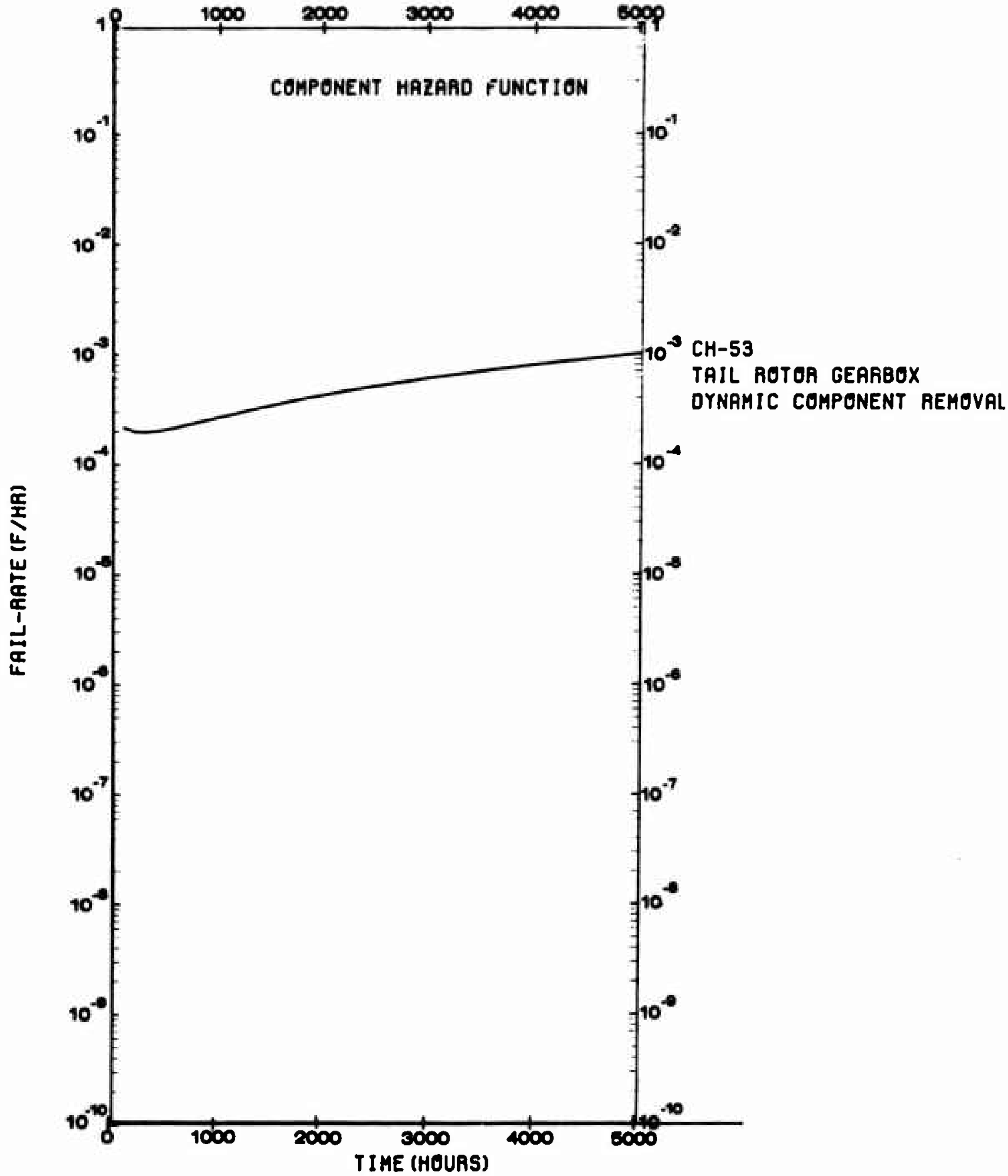

Figure 69. Improved CH-53 Tail Rotor Gearbox Dynamic Component Removal Hazard Function.

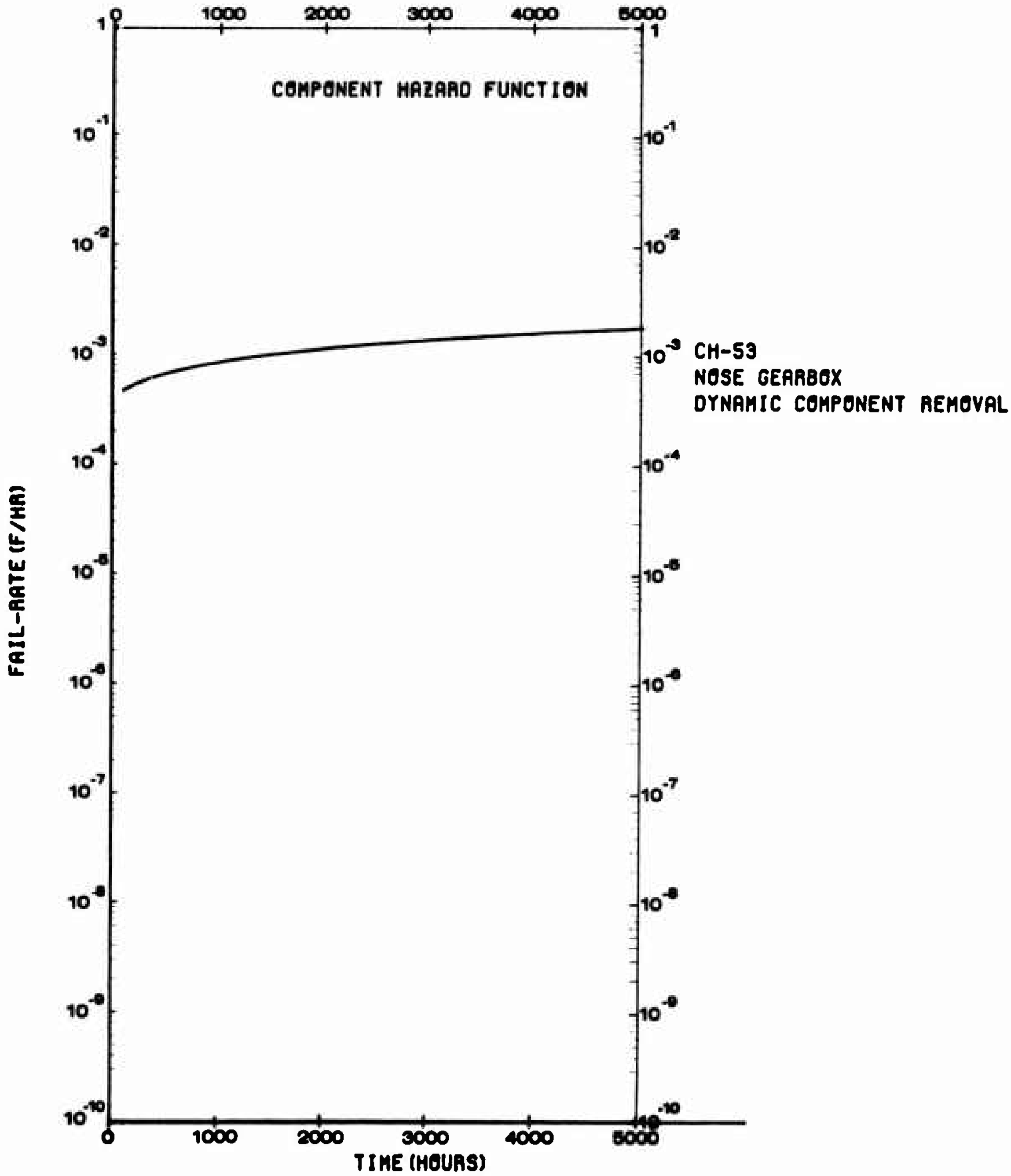

Figure 70. Improved CH-53 Nose Gearbox Dynamic Component Removal Hazard Function.

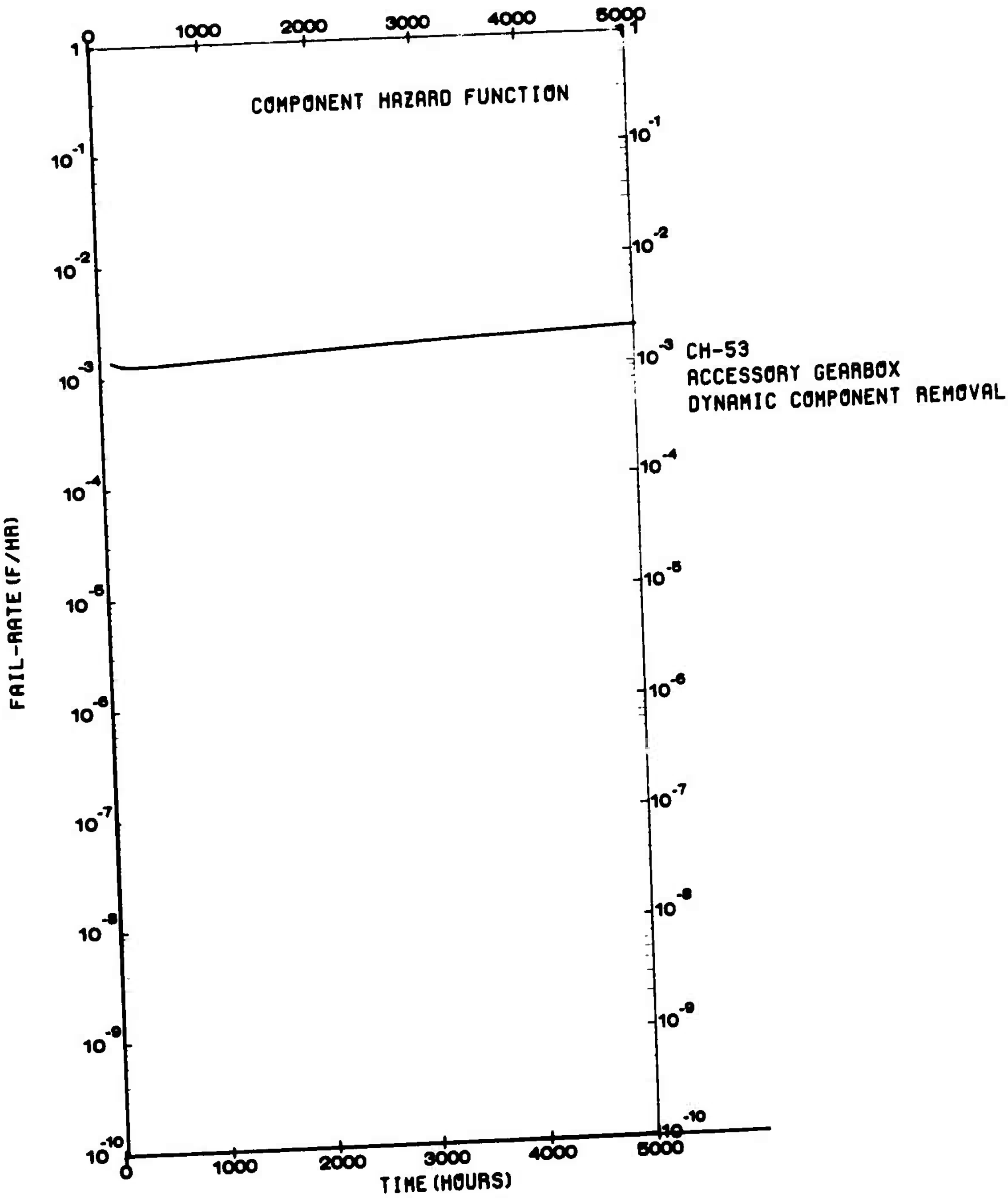

Figure 71. Improved CH-53 Accessory Gearbox Dynamic Component Removal Hazard Function.

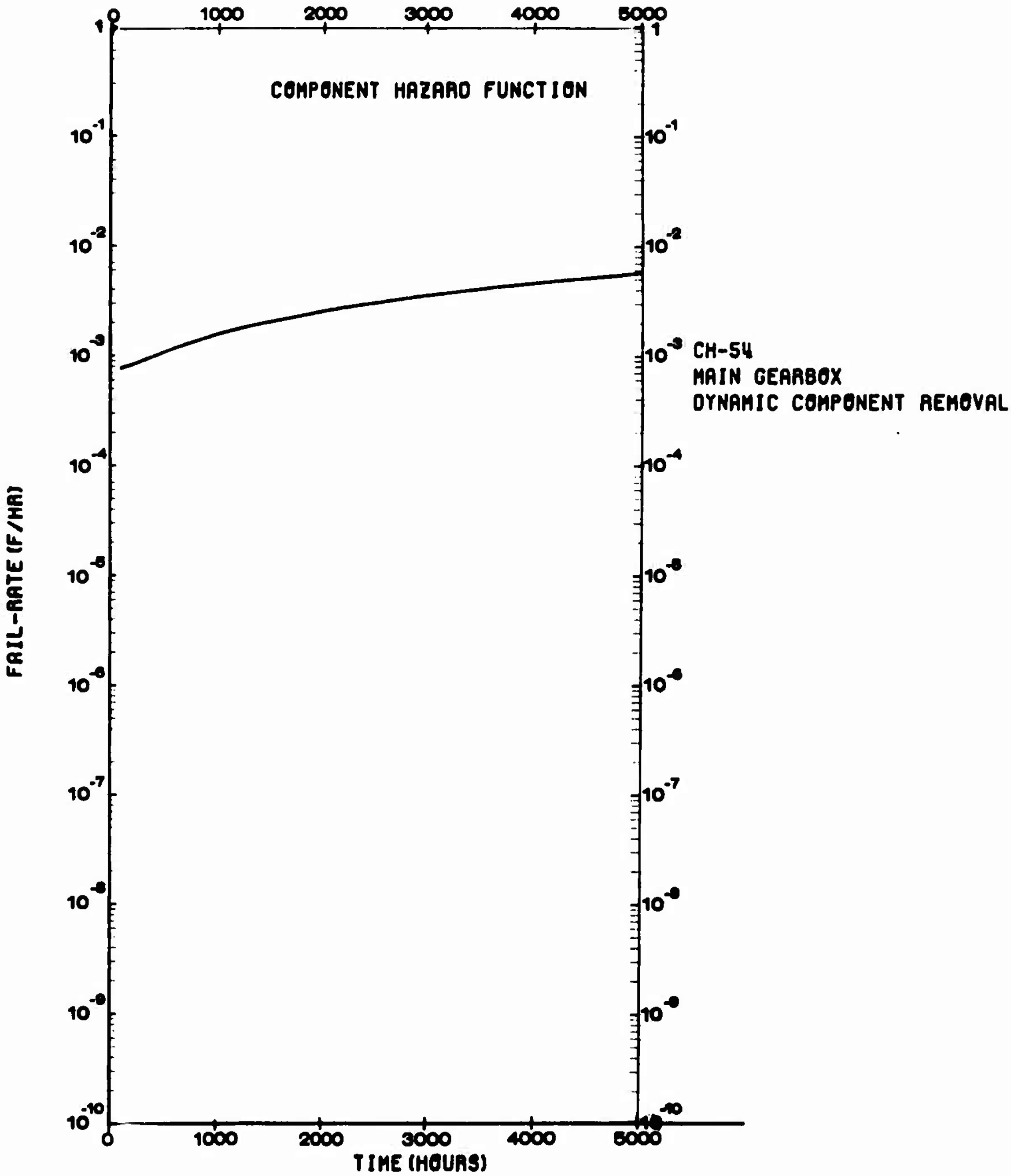

Figure 72. Improved CH-54 Main Gearbox Dynamic Component Removal Hazard Function.

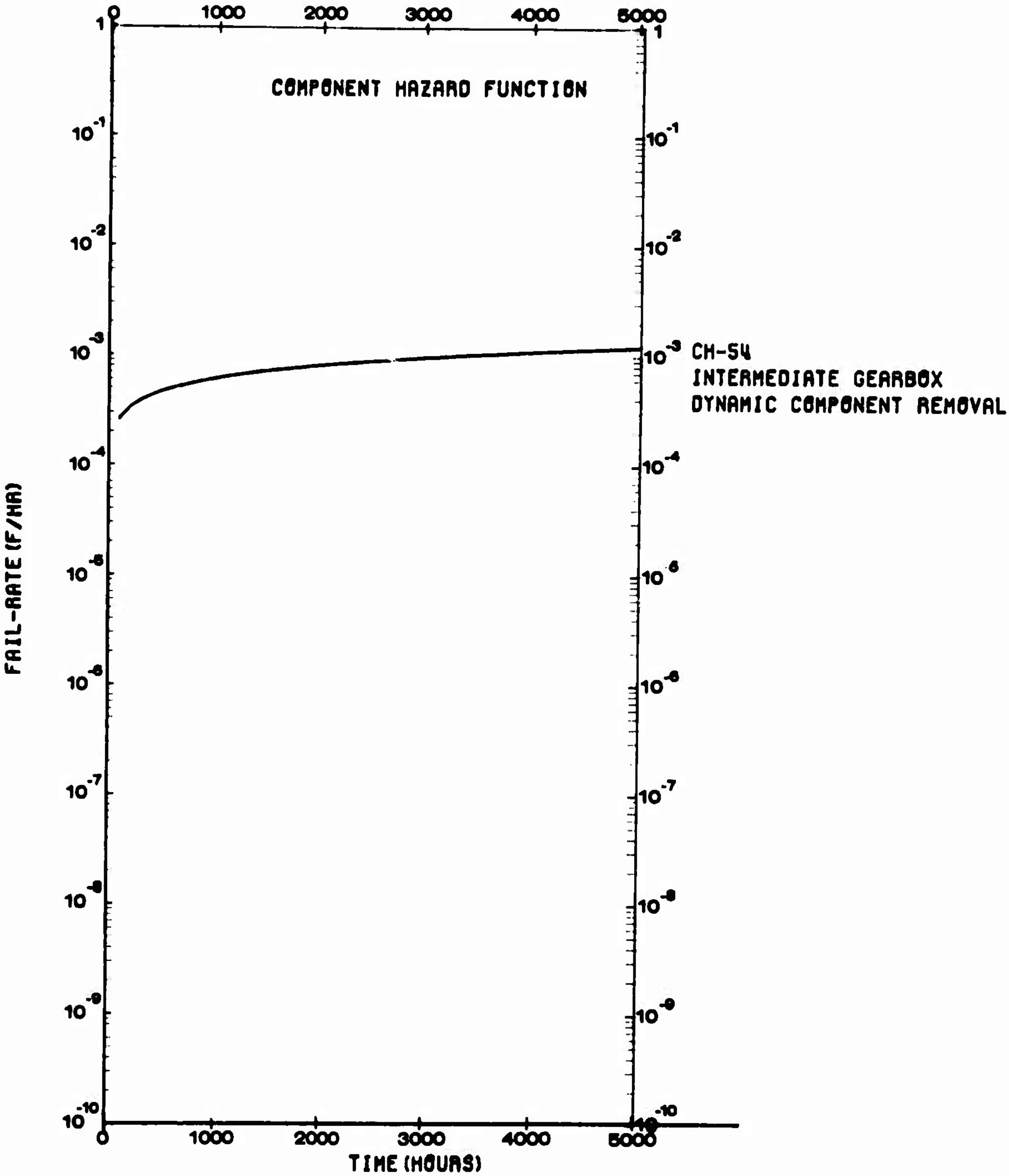

Figure 73. Improved CH-54 Intermediate Gearbox Dynamic Component Removal Hazard Function.

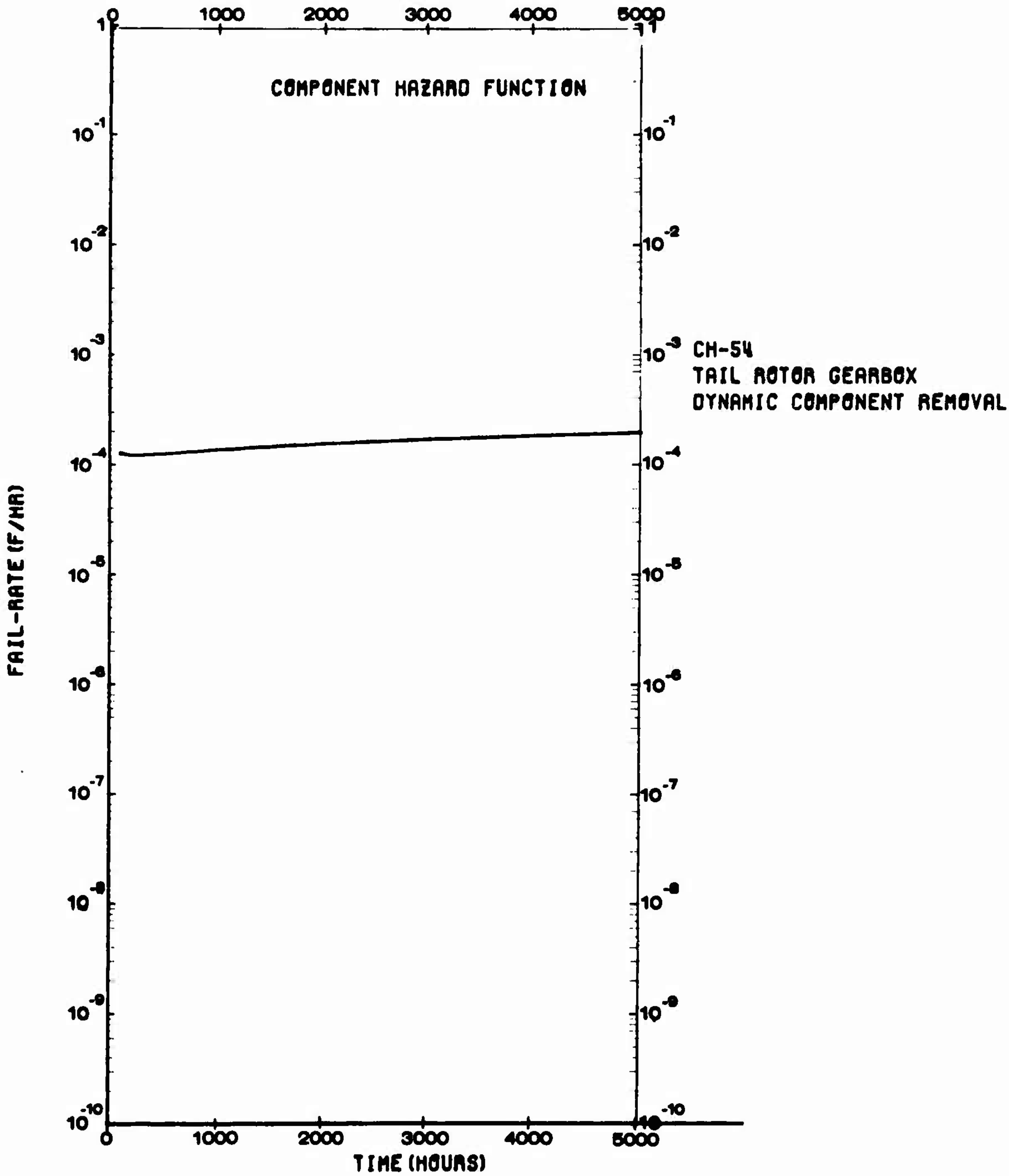

Figure 74. Improved CH-54 Tail Rotor Gearbox Dynamic Component Removal Hazard Function.

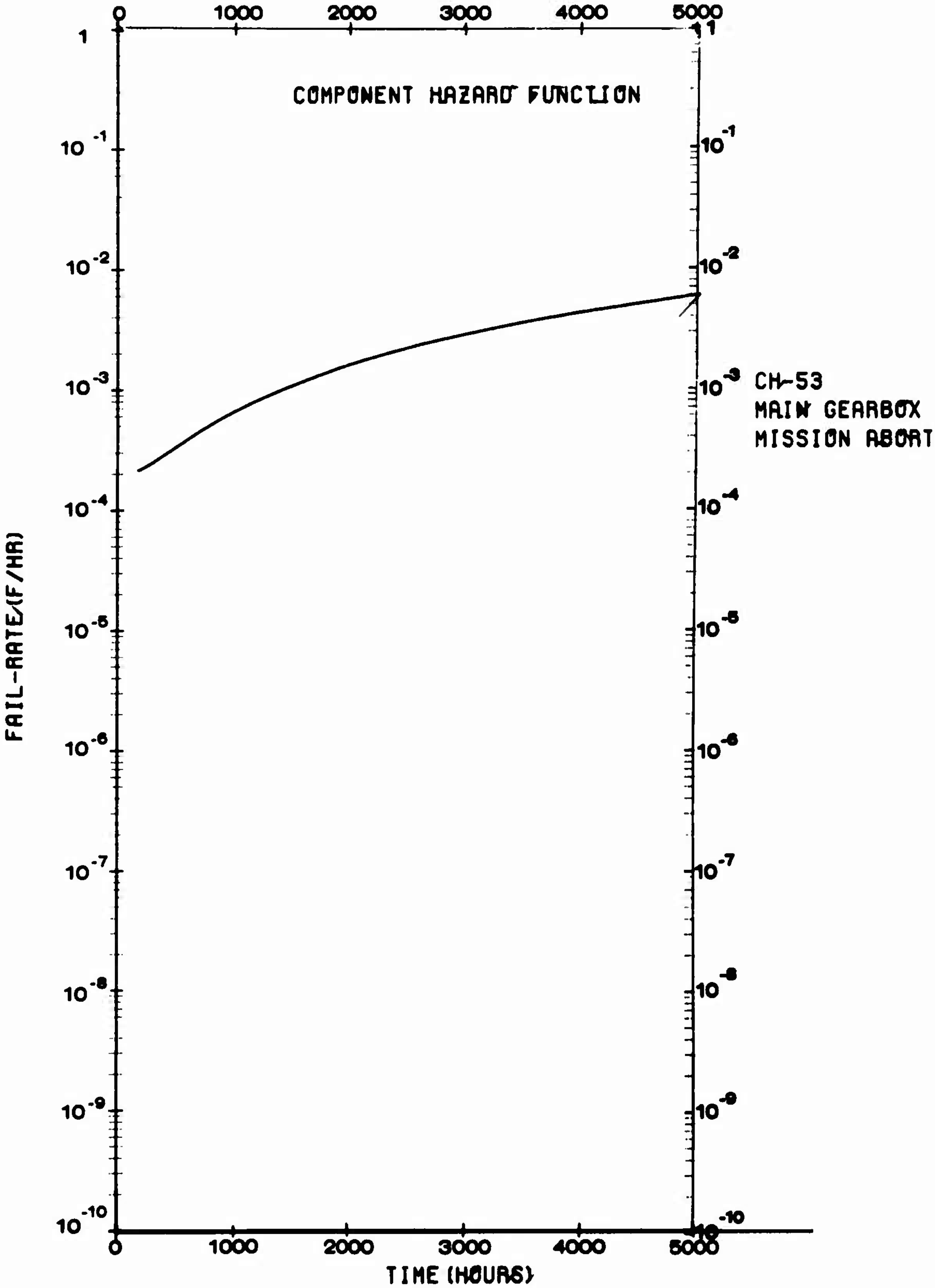

Figure 75. Improved CH-53 Main Gearbox Mission Reliability Hazard Function.

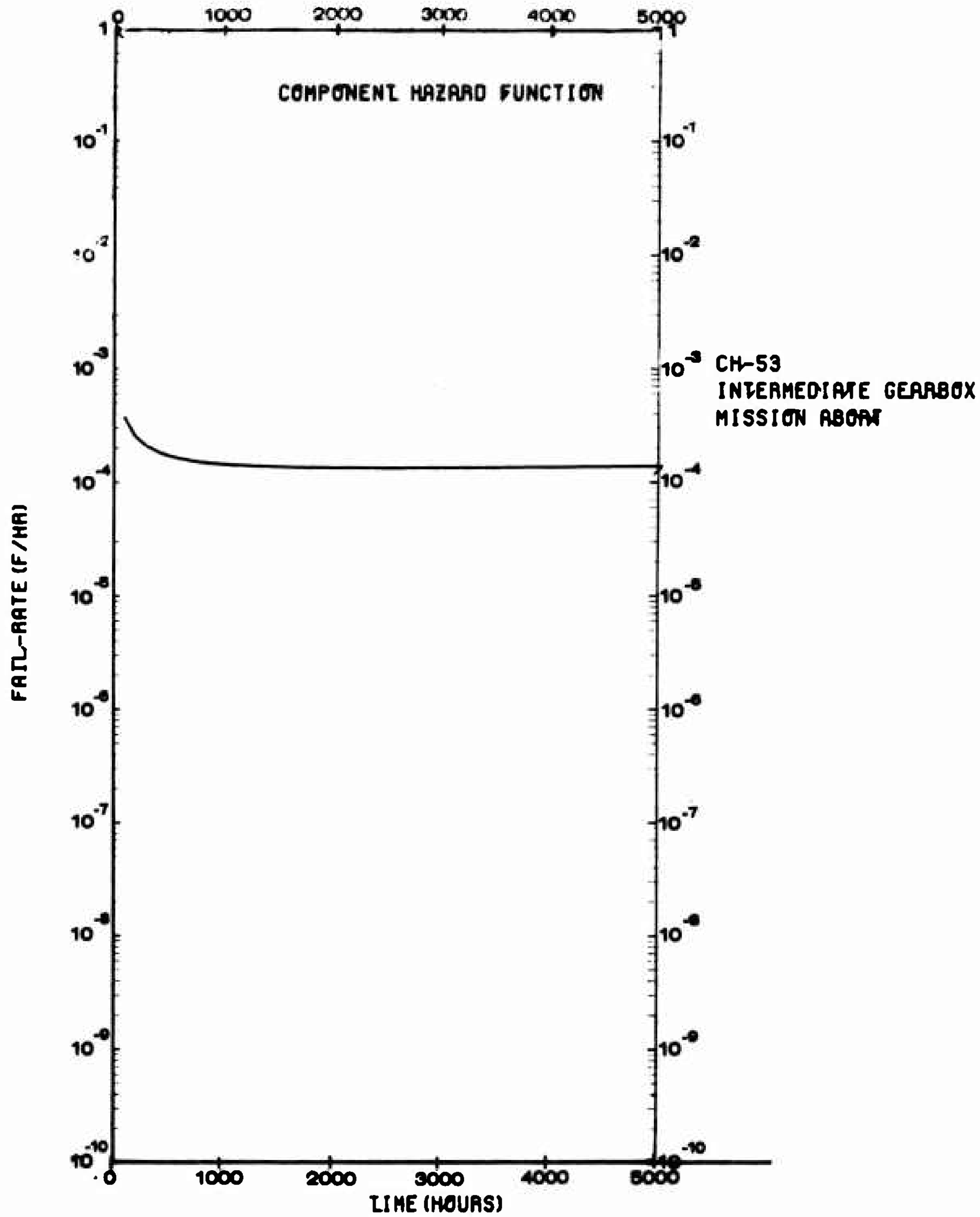

Figure 76. Improved CH-53 Intermediate Gearbox Mission Reliability Hazard Function.

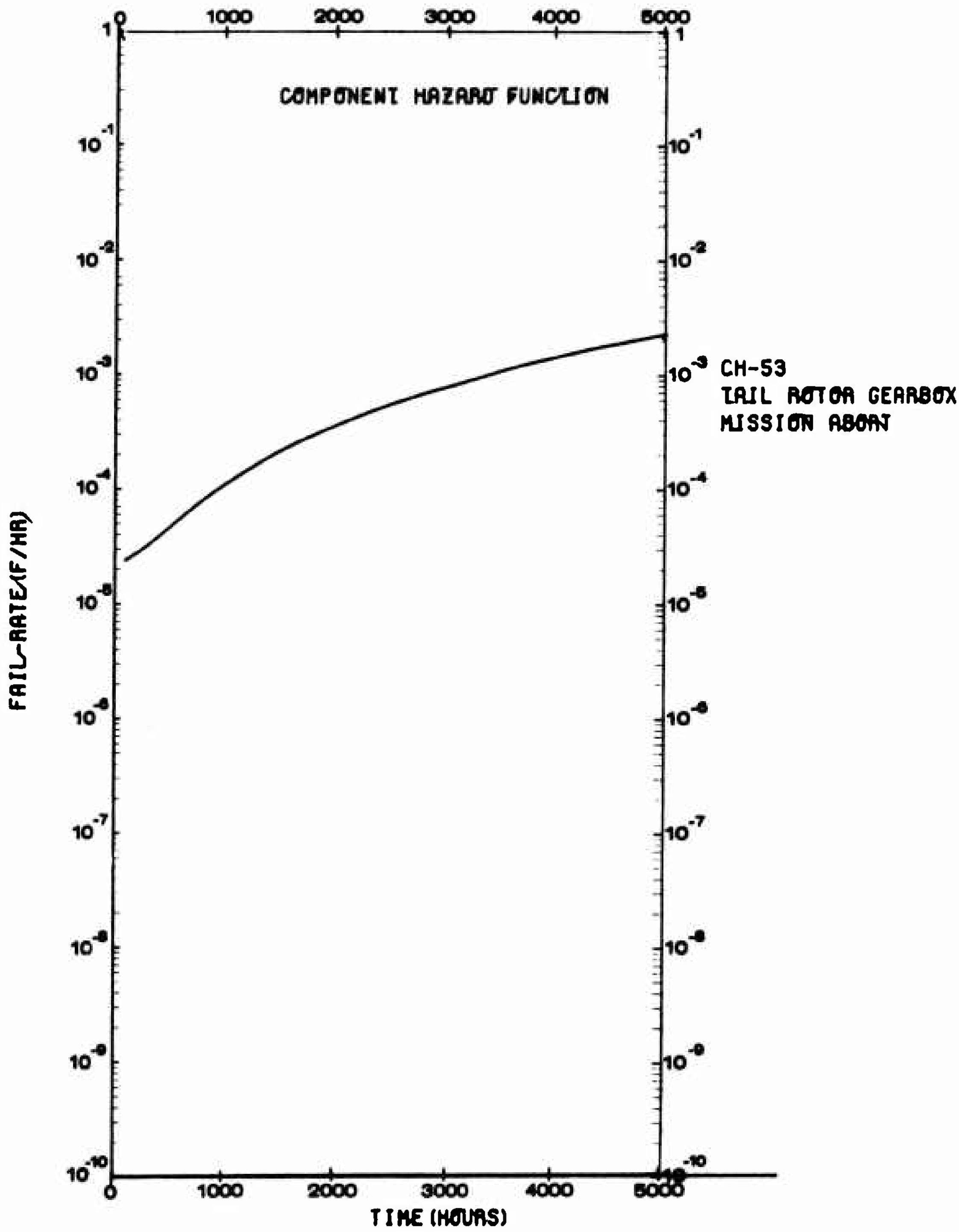

Figure 77. Improved CH-53 Tail Rotor Gearbox Mission Reliability Hazard Function.

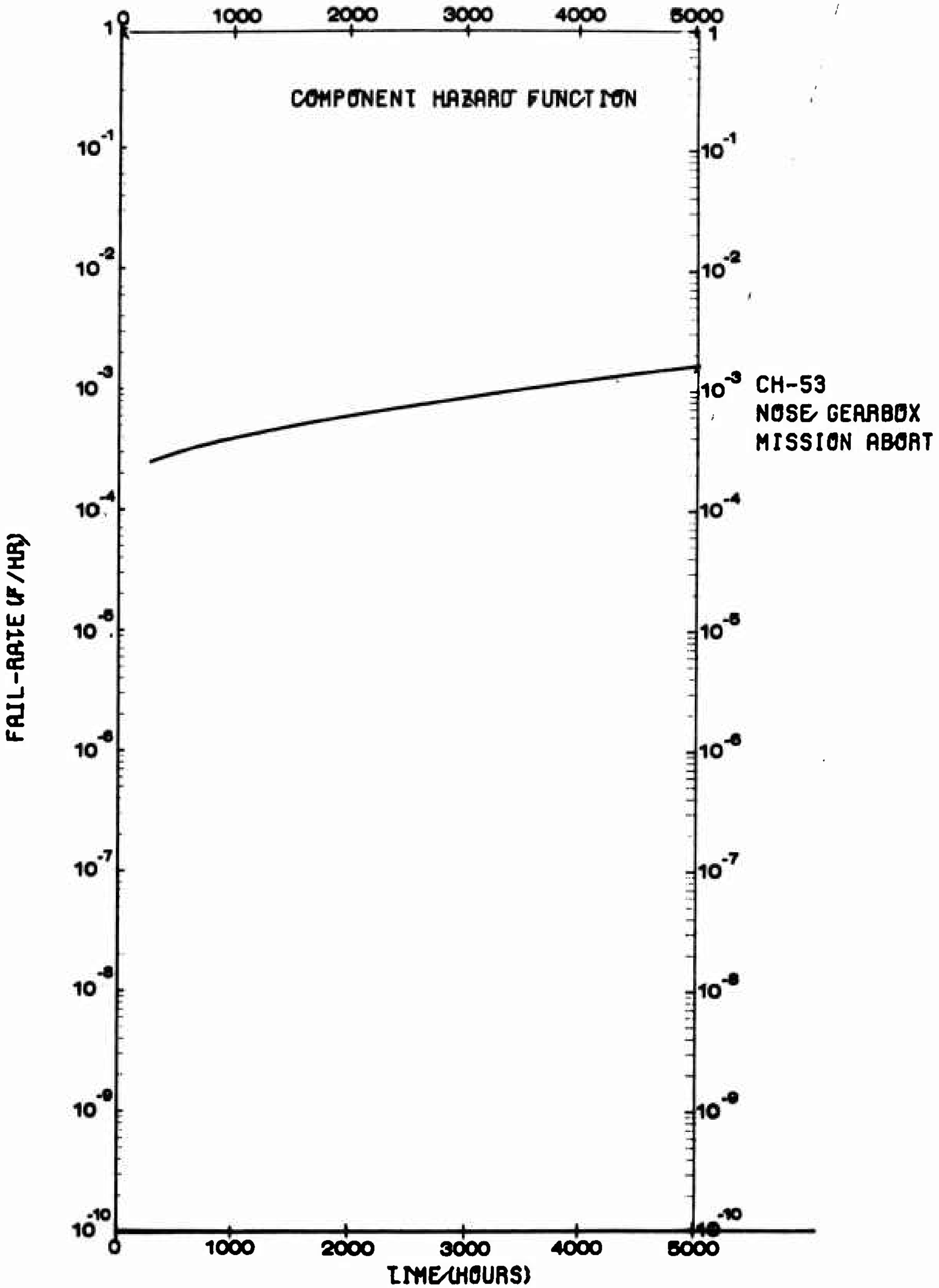

Figure 78. Improved CH-53 Nose Gearbox Mission Reliability Hazard Function.

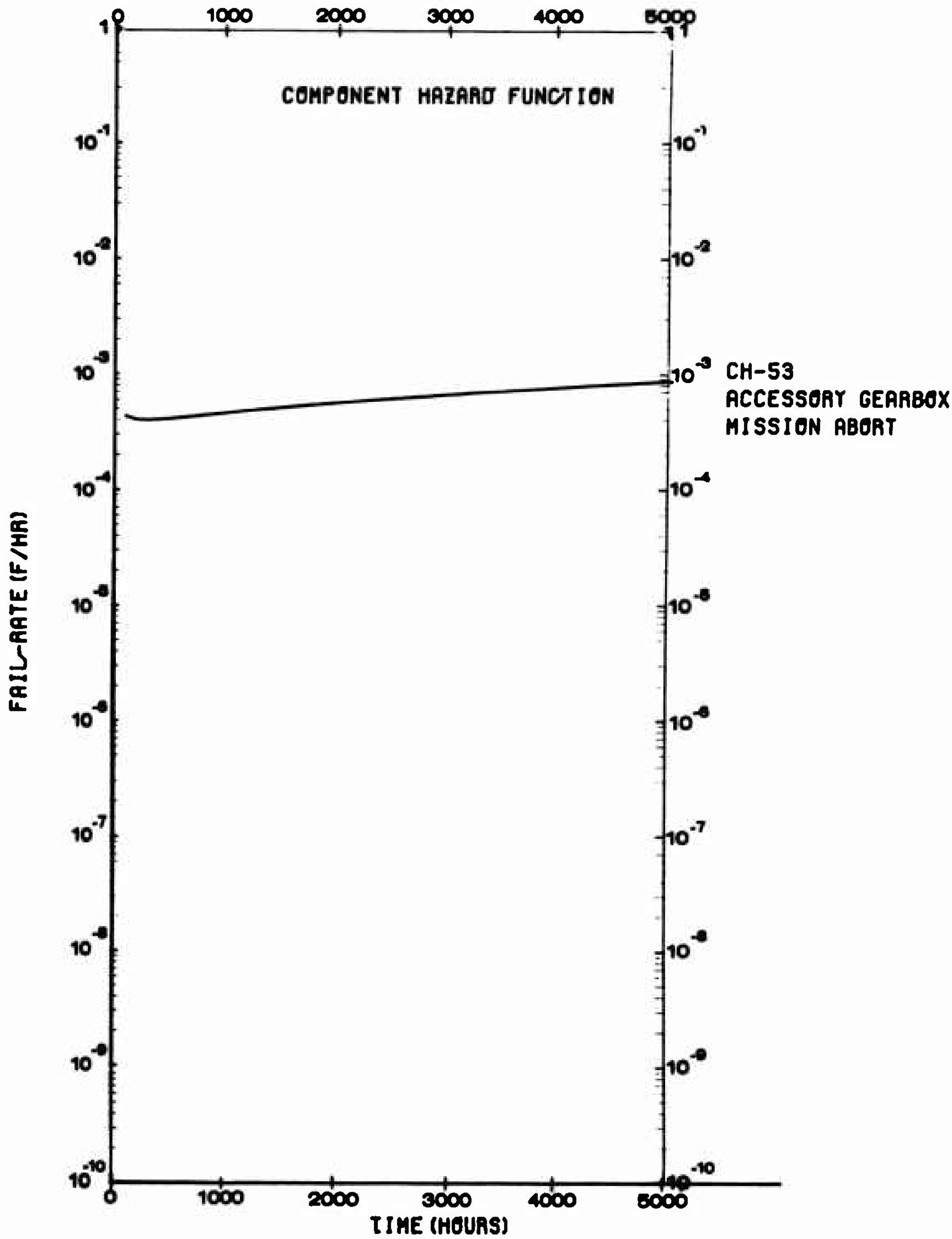

Figure 79. Improved CH-53 Accessory Gearbox Mission Reliability Hazard Function.

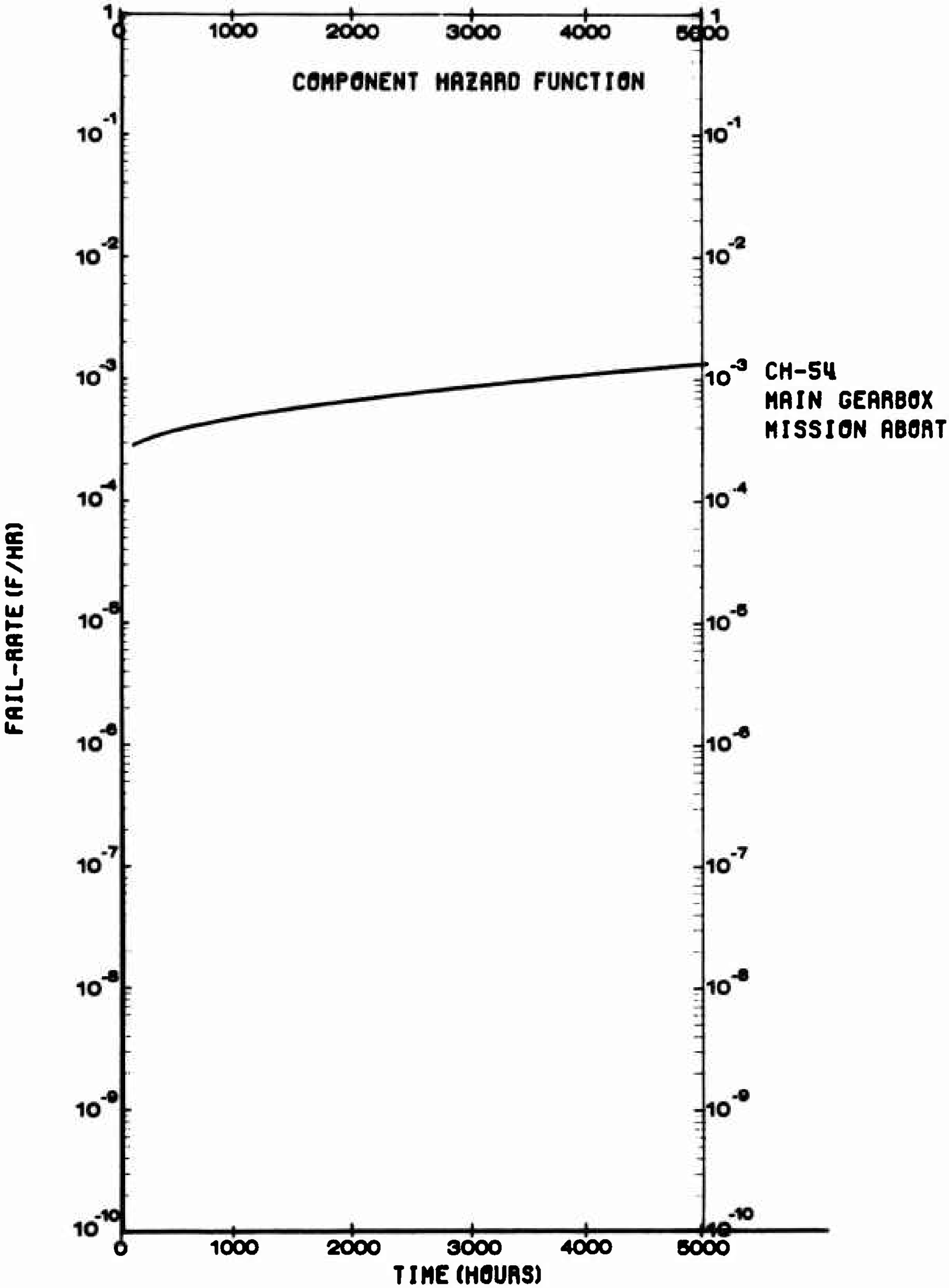

Figure 80. Improved CH-54 Main Gearbox Mission Reliability Hazard Function.

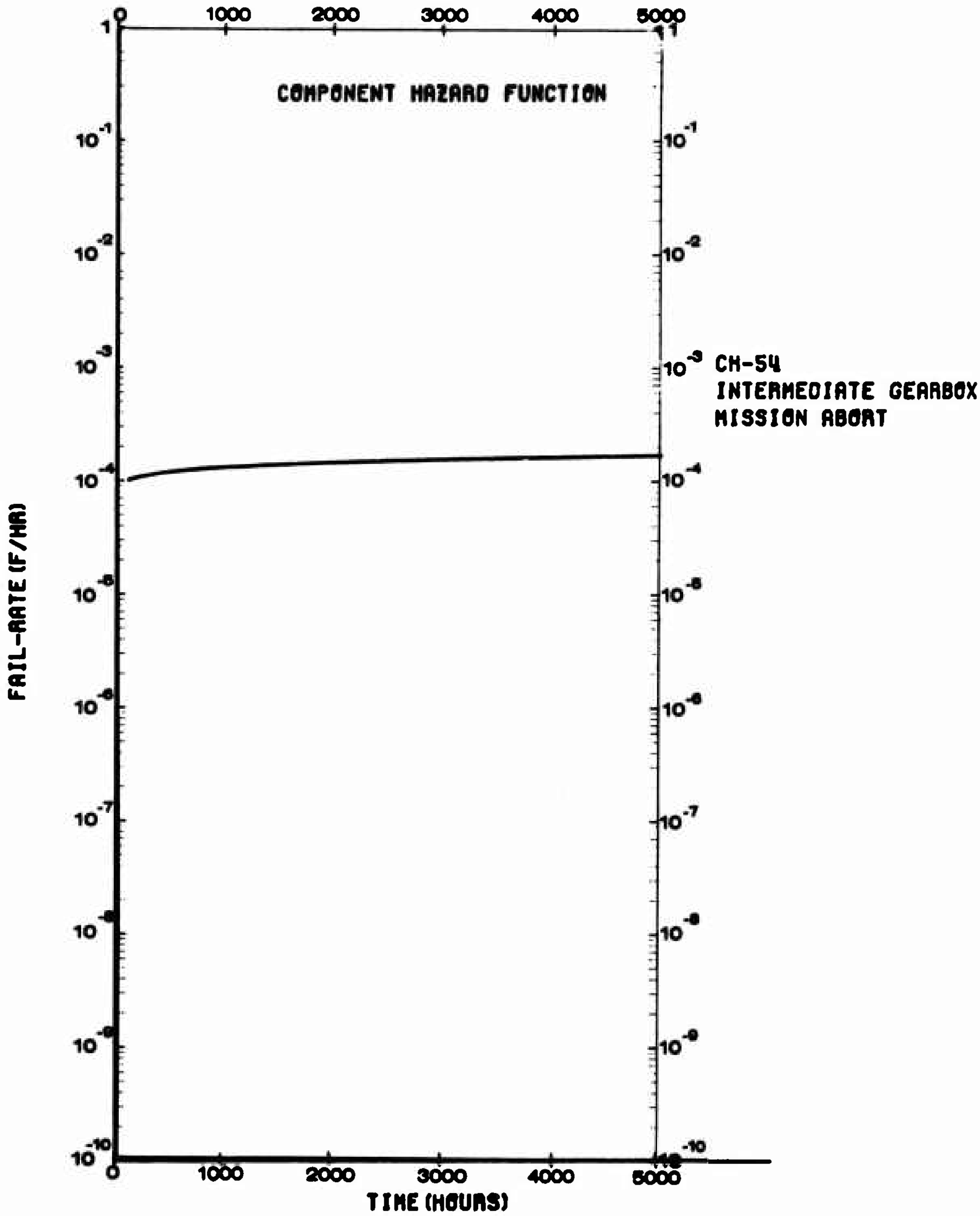

Figure 81. Improved CH-54 Intermediate Gearbox Mission Reliability Hazard Function.

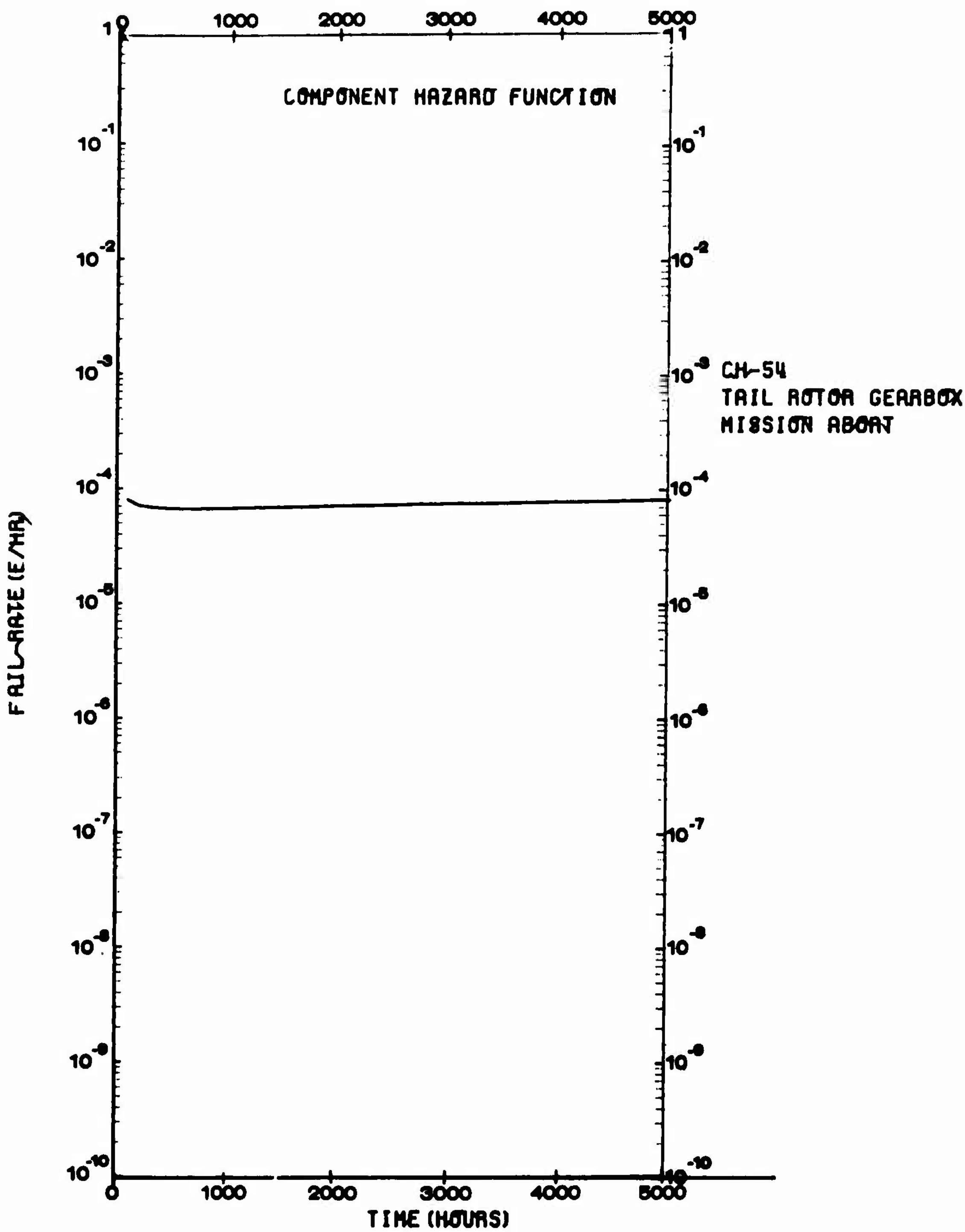

Figure 82. Improved CH-54 Tail Rotor Gearbox Mission Reliability Hazard Function.

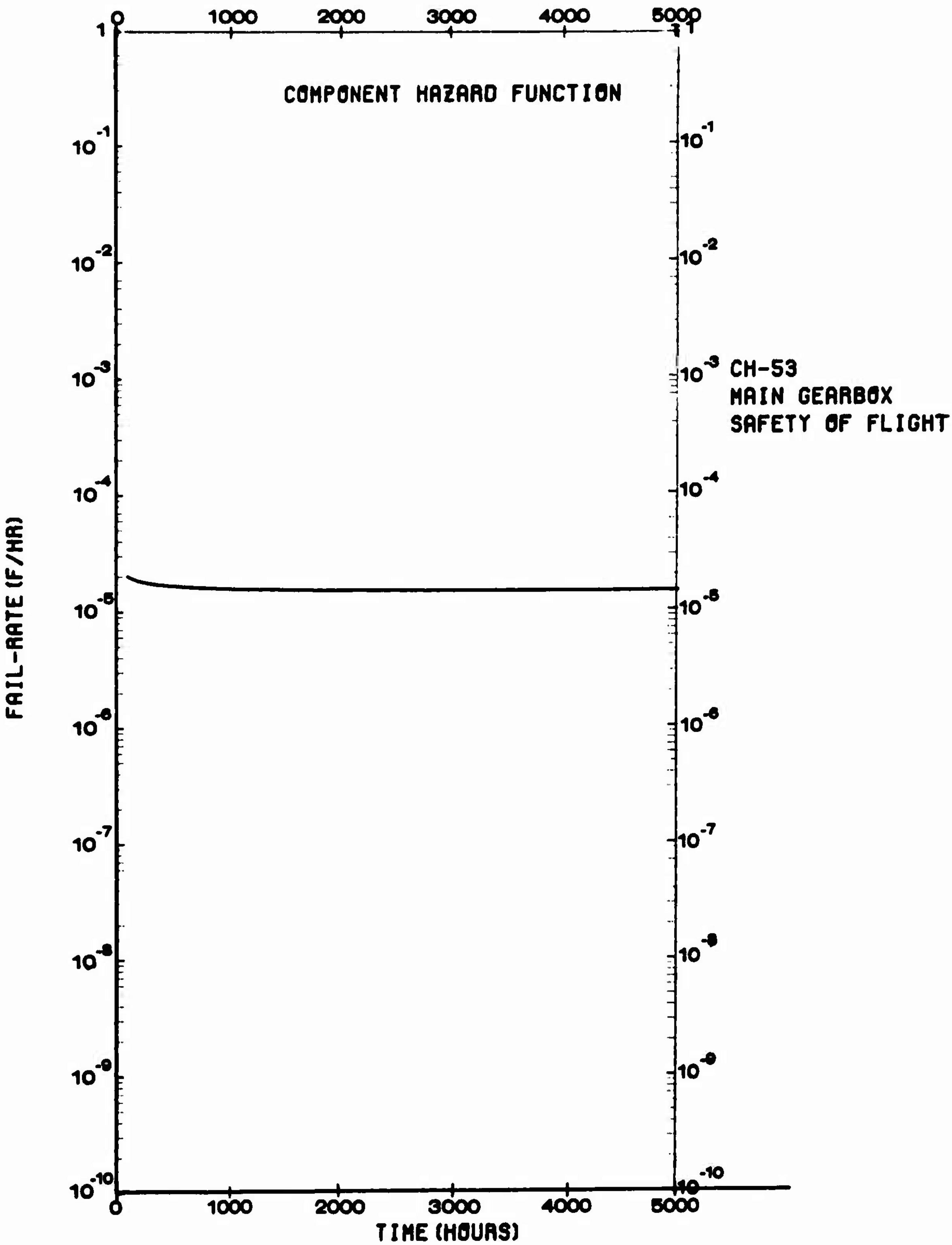

Figure 83. Improved CH-53 Main Gearbox Safety-of-Flight Hazard Function.

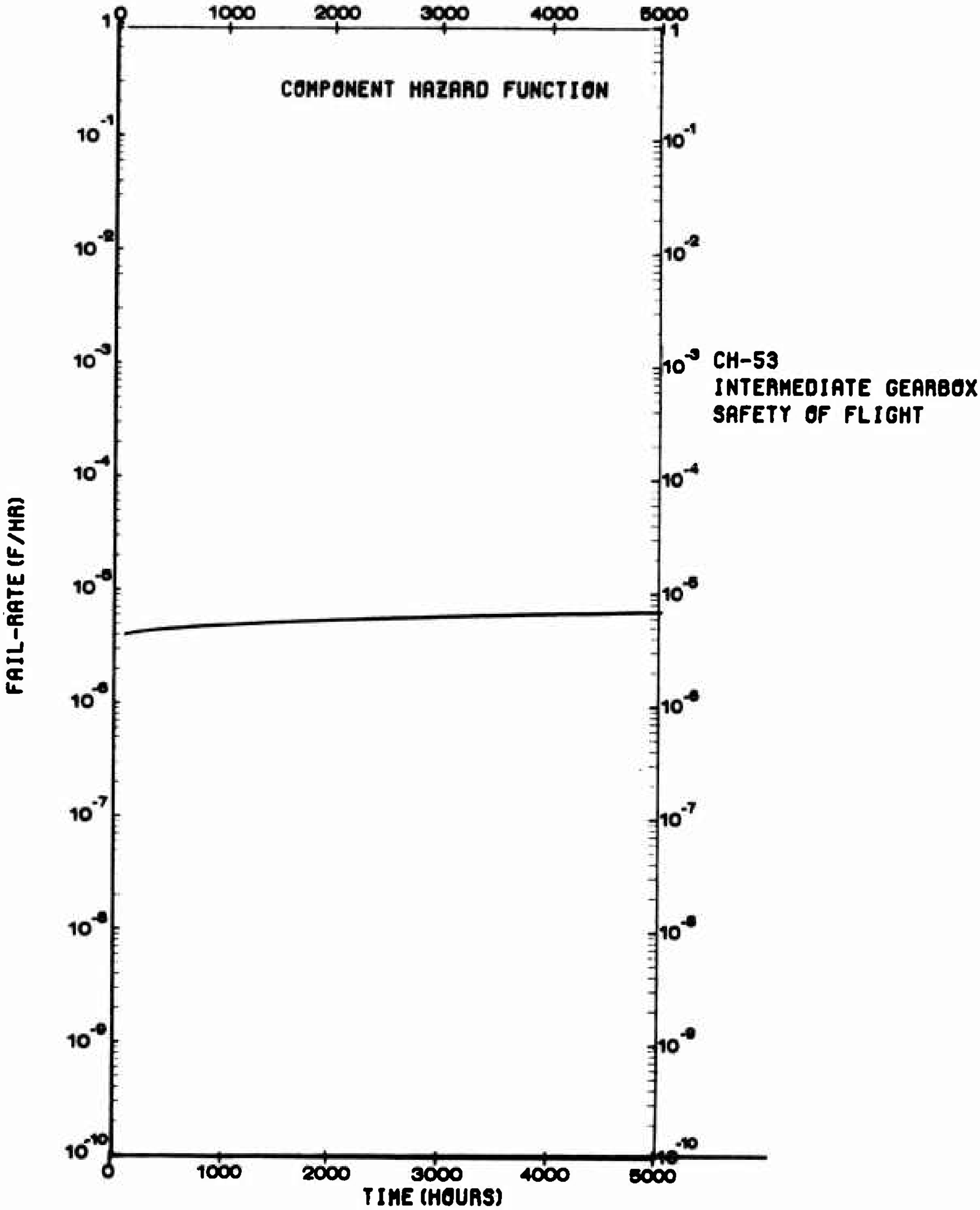

Figure 84. Improved CH-53 Intermediate Gearbox Safety-of-Flight Hazard Function.

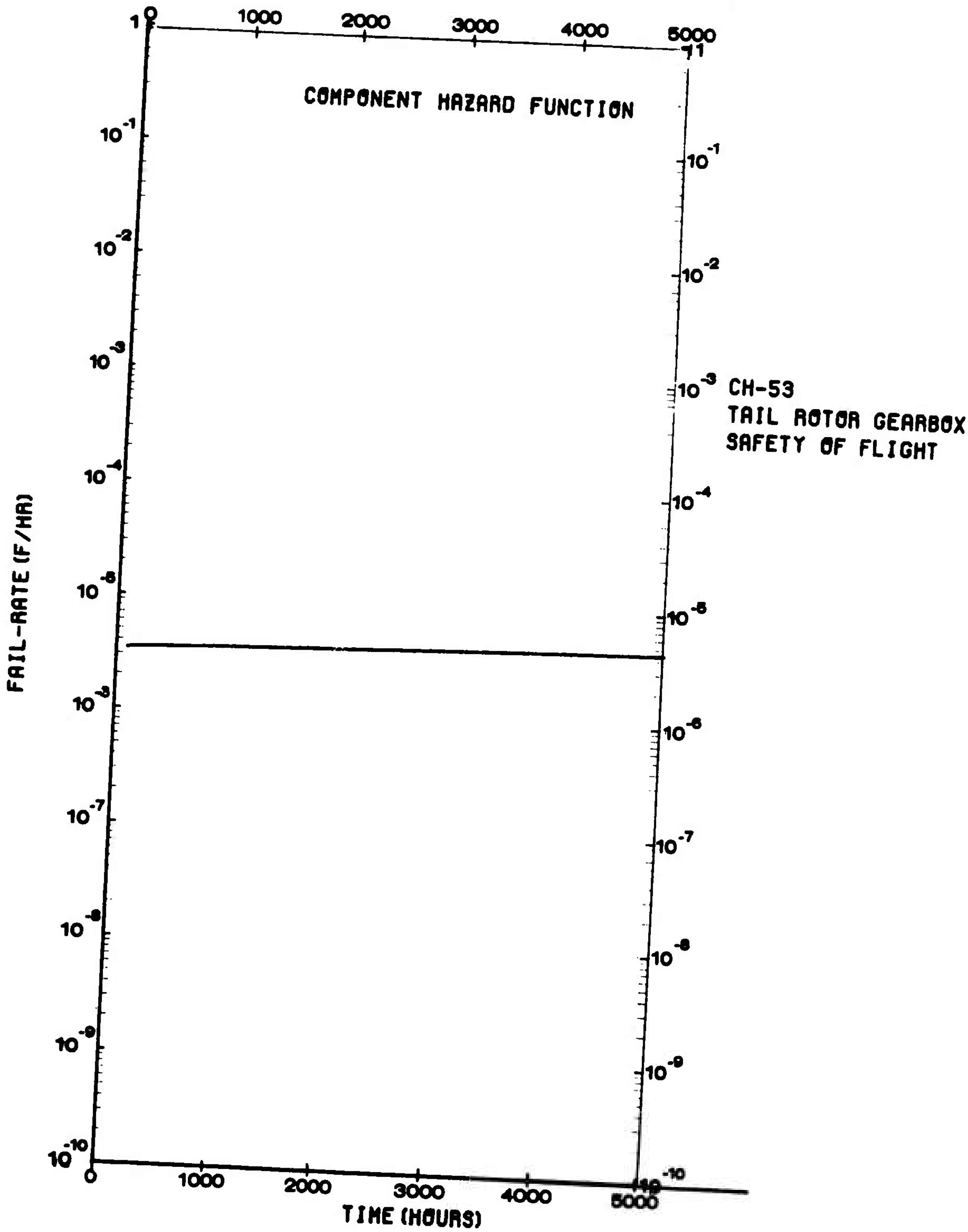

Figure 85. Improved CH-53 Tail Rotor Gearbox Safety-of-Flight Hazard Function.

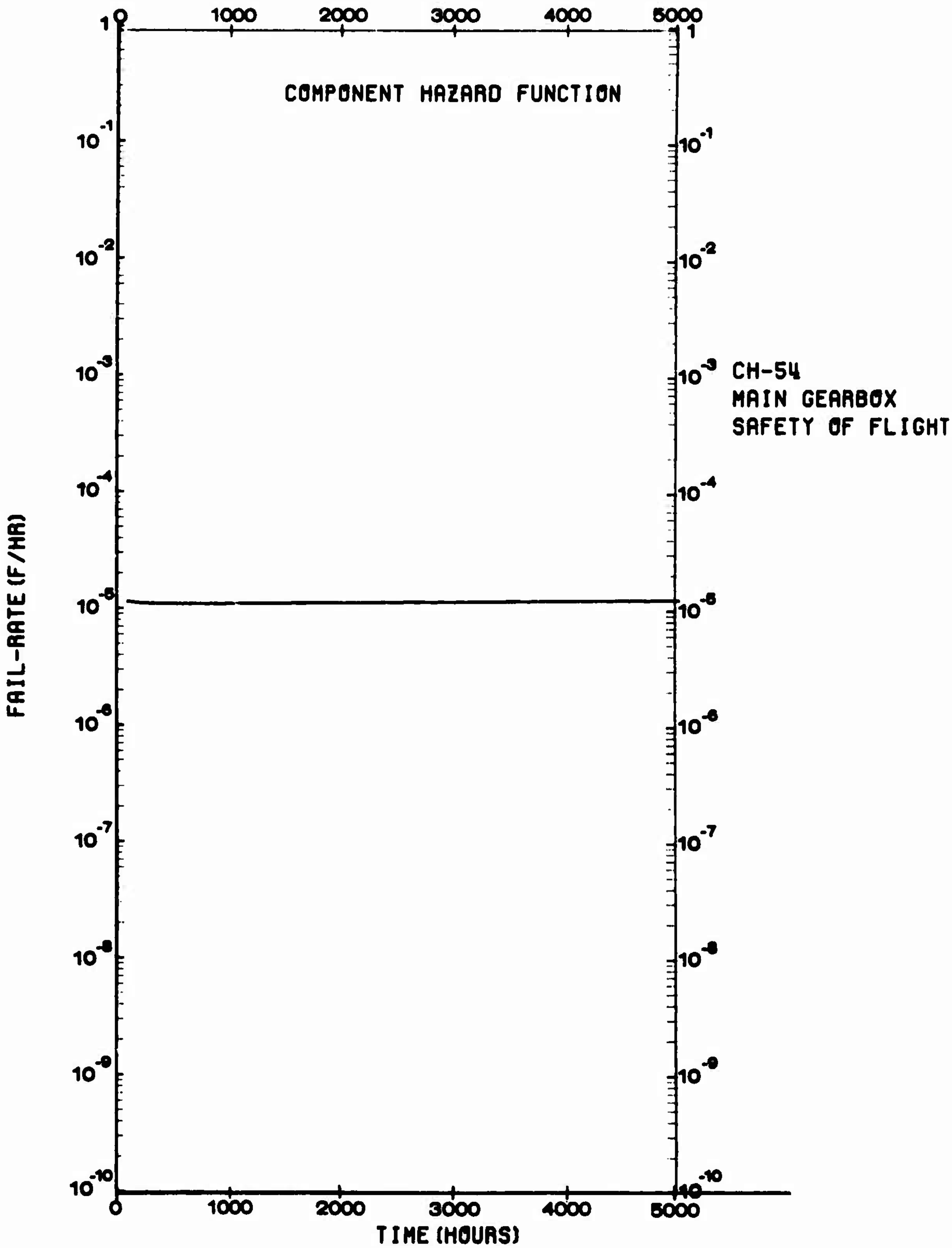

Figure 86. Improved CH-54 Main Gearbox Safety-of-Flight Hazard Function.

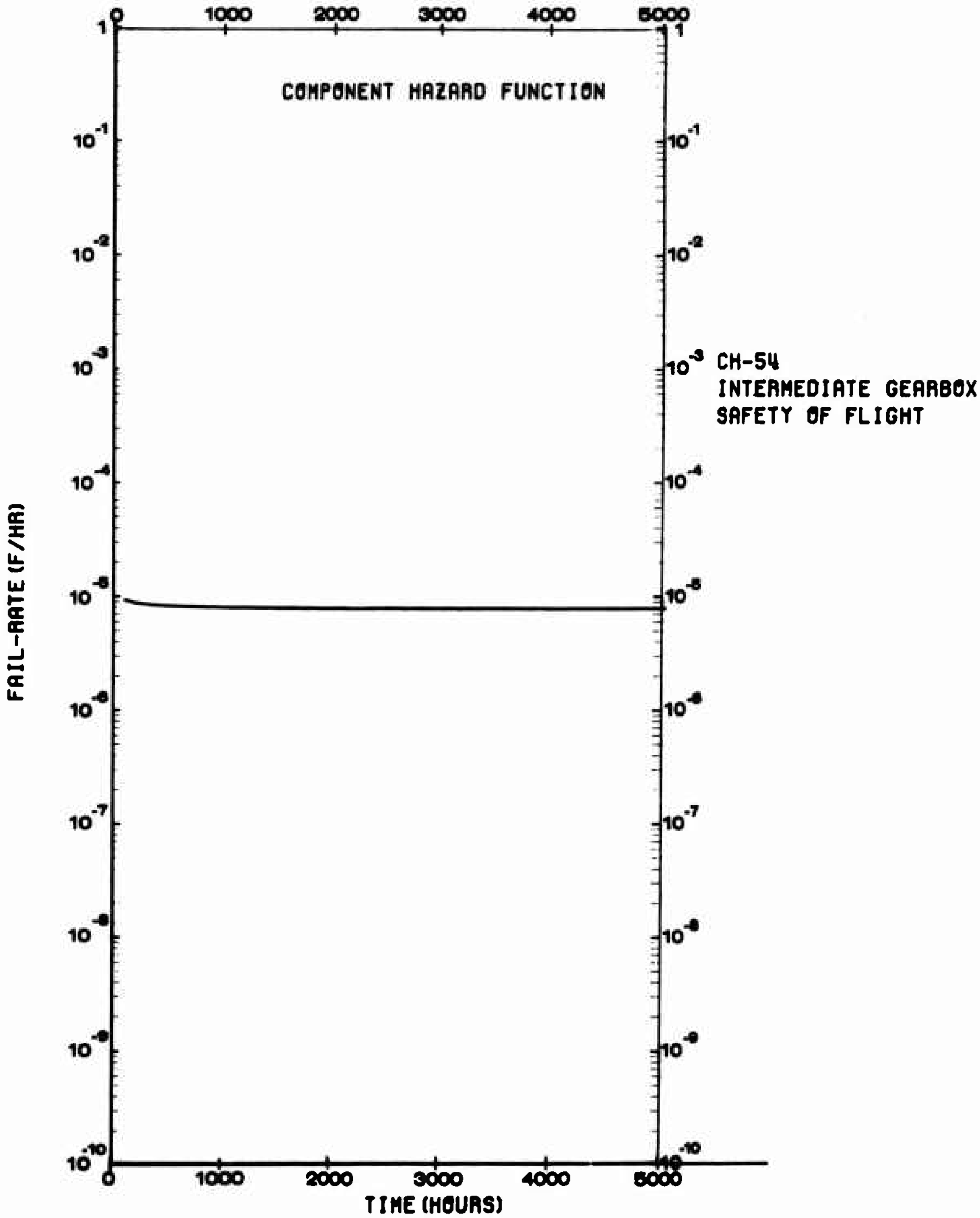

Figure 87. Improved CH-54 Intermediate Gearbox Safety-of-Flight Hazard Function.

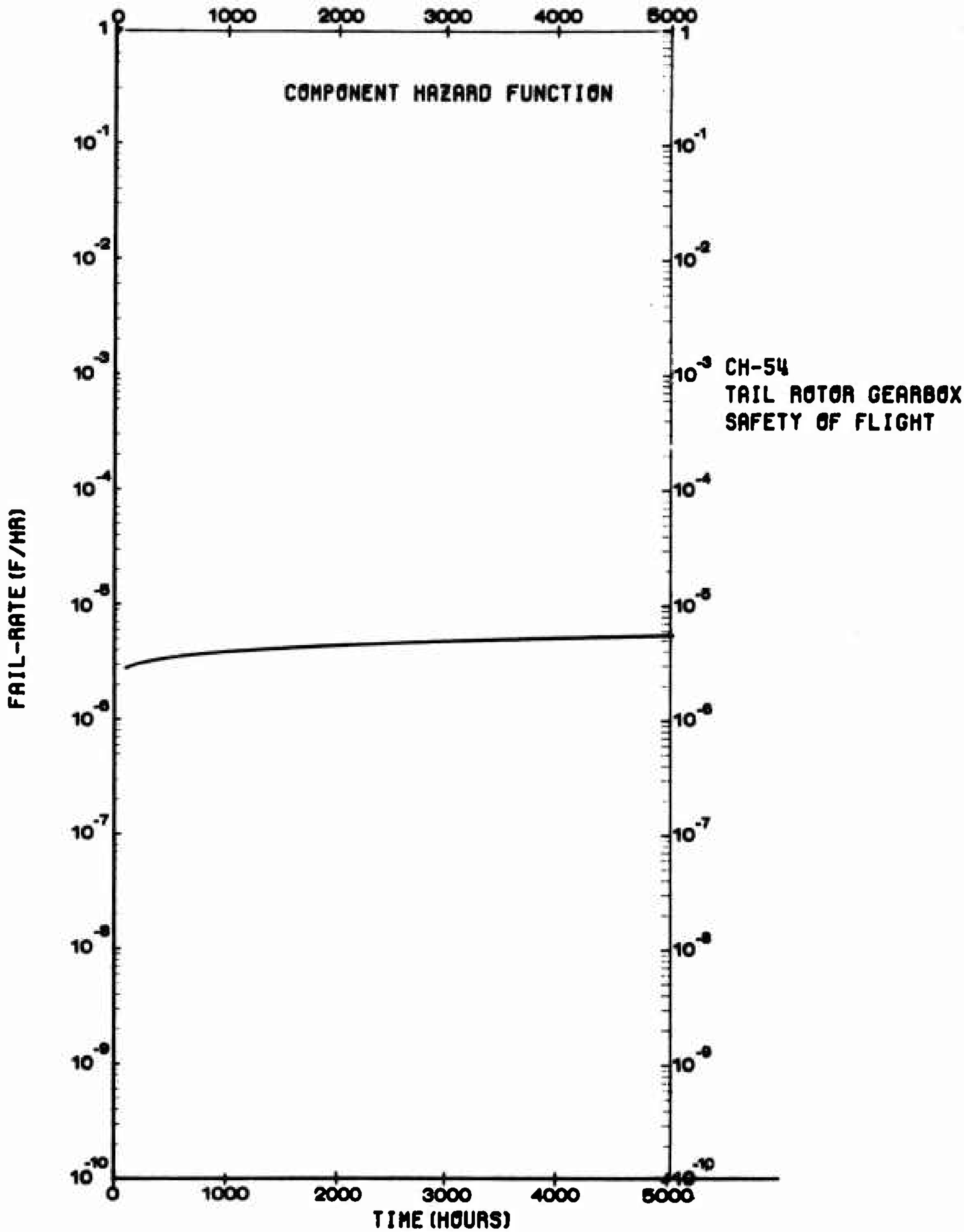

Figure 88. Improved CH-54 Tail Rotor Gearbox Safety-of-Flight Hazard Function.

Any data collection effort must have failure analyses performed to accurately assess any gearbox removals where failure is suspected. Furthermore, failures must be categorized so that priorities among failure modes can be weighted. Hazard functions could then be constructed with the techniques that are used to establish hazard function parameters for failure modes with experience data.

3.4 ANALYTICAL TECHNIQUES

In future designs, it is recommended that the drive train's dynamic response and in-plane response of all gears be evaluated to properly account for each gearbox's operation in the intended service environment. The benefit of such knowledge would be to better direct any development testing, to place weight where weight is needed, and to allow careful assessment and understanding of any trade-offs that are intended. The actual techniques could be empirical to reduce the cost involved. However, if empirical techniques are used, the boundary conditions which apply must be stated and well understood.

Many of the operating stresses that are experienced in the life of a gearbox are in response to demands from the engine, and the main and tail rotor head's moments and forces. They excite a complex network of masses, springs, and dashpots that characteristize the gearbox's dynamic response. The resultant frequency response of these step inputs is a measure of the dynamic forces that could be present throughout the gearbox. Such forces can produce low cycle fatigue or even almost instantaneous failure if not accounted for by the design. Some of these forces will be present only a small percentage of the time. As a result, to properly evaluate stresses that may exist on each component, the dynamic response of the gearbox must be understood.

The actual stresses that drive train gears experience are not a set of concentrated loads. Each gear is not a rotating rigid body. Instead, gear teeth experience load distributions and bending moments which cause them to bend and create different mode shapes. While such stresses can be evaluated in terms of a maximum and a minimum, the structural damage incurred must reflect the effect of all. As a result, to properly account for the operating environment of gears, their in-plane dynamic response has to be evaluated.

4.0 CONCLUSIONS AND RECOMMENDATIONS

On-condition maintenance of CH-53/54 gearboxes is feasible with today's technology on the basis of their projected hazard functions at 5000 hours. Current inspection techniques and diagnostic devices are adequate for implementing an on-condition maintenance policy. The fact that data for this study was obtained from aircraft that flew in Vietnam and experienced overtorque situations reinforces the practicality of on-condition maintenance.

Certain design improvements are recommended before the implementation of on-condition maintenance, though many are not essential. Only those improvements which are needed to retain the lubricant in grease lubricated splines and to reduce the stresses in the housing of intermediate and tail rotor gearboxes are essential. Other improvements are desirable to improve product reliability and increase overall effectiveness of the CH-53/54 gearboxes. The fact that only a limited number of improvements are recommended reflects the fact that gearbox reliability is governed by relatively few failure modes. Generally, three or less failure modes are responsible for a majority of each gearbox's failures.

Concurrent with the initiation of on-condition maintenance, it is recommended that data collection for gearboxes that are on-condition be instituted. This will verify the failure rate behavior predicted by this study and provide the necessary feedback of information should any unforeseen problems arise. This study indicates, however, that virtually all failure modes that significantly affect gearbox reliability behavior at 5000 hours are currently known. As a result, the actual failure rate behavior will be governed by the impact of improvements on the existing hazard functions.

Future design efforts should evaluate the dynamic response of aircraft gearboxes as well as the in-plane response of drive train gears. This would benefit detail component design by providing an understanding of the dynamic environment and aid development test planning by providing better direction.

Future gearbox designs should be evaluated for on-condition by the methodology developed in this study. Data from Boeing Vertol's previous study, USAAMRDL contract DAAJ02-72-C-0068, and Bell Helicopter's current study, USAAMRDL contract DAAJ02-74-C-0060, should be integrated with this study's to permit a universal design philosophy for designers to apply in the future. This would allow gearbox reliability of future Army helicopters to be understood and incorporated in the design.

APPENDIX A

ANALYTICAL TECHNIQUE FOR ESTABLISHING HAZARD FUNCTIONS

A.1.0 INTRODUCTION

On-condition maintenance criteria are evaluated by establishing hazard functions for safety-of-flight, mission reliability and dynamic component removal failures for each gearbox. Hazard function generation begins by defining and categorizing generic component failure modes (safety-of-flight, mission reliability, or dynamic component failure mode) in terms of their possible effect on aircraft performance. The impact of maintenance inspections and fault warning systems is then evaluated to determine their ability to recategorize generic component failure modes. Resulting from this effort is a set of failure modes which comprise each failure category. Hazard functions are then established for each failure mode in every category from either experience data or by various estimation methods when no experience data are available. Finally, all hazard functions of a particular category are combined and plotted.

A.1.1 FAILURE MODE AND EFFECT ANALYSIS (FMEA)

The failure mode and effect analysis (FMEA) determines drive system failure modes and categorizes their effect on aircraft reliability performance. This study considers three general categories of failure modes for a particular gearbox. The criterion for each category is given in Table 1 in the main body of the report.

The criteria for a safety-of-flight failure mode are more encompassing than usually encountered in doing an FMEA. As a rule, those failure modes which cause only an immediate forced landing are not categorized as safety of flight. Rather, they are categorized as a mission reliability failure mode.

Before commencing the FMEA, the general criteria of Table 1 were translated into effects on drive system performance so that it could be applied to individual gearbox performance. Those failure modes which potentially might result in the loss of main rotor power, or tail rotor power or complete loss of all hydraulic and electrical power were tentatively categorized as safety-of-flight failure modes. Failure modes which activate fault warning systems were categorized as mission reliability failure modes. Finally, failure modes which could result in gearbox removal were categorized as a dynamic component removal failure mode.

The FMEA was conducted by first considering the failure modes of each gearbox component. Each failure mode was analyzed to determine its effect on assembly, gearbox, drive system, and aircraft performance. When a failure mode could be placed in several categories depending upon its severity, the worst possible was chosen first. Maintenance inspections and fault warning systems were then analyzed to determine their applicability. Potential safety-of-flight failure modes that could be detected by fault warning systems and give the pilot an ample warning of impending failure were reclassified as mission reliability failure modes. Potential safety-of-flight failure modes that could be detected by maintenance inspections which eliminate their occurrence in flight were reclassified as dynamic component removal failure modes. If an inspection did not completely eliminate the possibility of a failure mode, it was not recategorized. Usually experience data permitted a reduction in the significance of such hazard function for the more severe categories. When no experience data were available, no reduction in the significance was assumed. At this point, the FMEA was documented as shown in Figure A-1.

In instances where a failure mode could be placed in several categories depending upon its severity, the worst case was first assumed. This permitted a minimal set of failure modes which comprise safety of flight and mission reliability categories to be defined. The lesser effects were then assumed to result in a lower category failure mode. As a result, a failure mode such as bearing spalling was placed in both the mission reliability failure and dynamic component removal failure categories.

When all the individual failure modes were analyzed and all the failure modes that comprise each category defined, they were summarized by generic component. The term generic component indicates a broad class of components. Bearings were divided into three generic components: ball bearings, cylindrical roller bearings, and tapered roller bearings. Gears were divided into two generic components: spiral bevel gears and spur gears. A listing of other gearbox generic components can be found in Section 2.1 of this report.

A.1.2 HAZARD FUNCTION GENERATION

Hazard functions describe how the failure rates associated with component failure modes behave with time. The technical approach that has been developed uses the hazard functions of individual generic component failure modes as building blocks to construct the gearbox level hazard function for each category of failure mode. The reliability distribution used to generate these is defined by the Weibull reliability function of the form $e^{-(\frac{t}{\theta})^{\beta}}$. The hazard functions computed specifically apply to a single failure mode. The β and θ which describe the hazard function as well as the reliability function are also computed.

Two types of hazard functions comprise each gearbox's hazard function. The first type applies to those failure modes with experience data. The second type applies to failure modes with no experience data due to the current gearbox's scheduled time-between-overhauls (TBO). The purpose of the last type is to provide an accounting of likely failure modes if the TBO's of existing components were extended to 5,000 hours. These two types of hazard functions will hereafter be denoted as experienced failure mode hazard functions and potential failure mode hazard functions respectively.

A component's reliability and its hazard function are related. The cumulative reliability, $R(t)$, is defined as the probability of a component's operating without failure between a time $T = 0$ and a time $T = t$. The hazard function, $h(t)$, is defined as the instantaneous failure rate of the

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS - SHEET "A"

AIR VEHICLE CH-53

SYSTEM Main Gearbox

ASSEMBLY Accessory Take-Off

DESIGN ______ DATE ______

SAFETY ______ DATE ______

HUMAN FACTORS ______ DATE ______

PREPARED BY B. Trustee

DATE ______ PAGE ______ OF ______

REVISION NO. ______ DATE ______

Name and Identification No.	Quantity Per System	Function	Failure Mode	Failure Detection Method	Failure Effect On		Failure Mode Category
					System	Air Vehicle	
Nut (65351-11189-101)	1	Clamp inner race of SB-1069 ball bearing and inner race of SB-1068 ball bearing to drive gear shaft shoulder, thereby maintaining axial position of accessory bevel gear (65351-11191).	Locking device loosens and causes nut to lose preload and back off. (Failure code 910)	Chip light activation.	Loss of gear shaft retention allows gear to move axially until contact is made with stationary housing.	Chip light prevents failure mode from progressing to complete gearbox failure.	II
Nut (65351-11197-101)	1	Clamp each tapered roller bearing inner race to gear shaft shoulder and preload bevel gear shaft tapered roller bearings, thereby maintaining axial position of accessory bevel take-off gear (65351-11195).	Locking assembly loosens and causes nut to lose preload and back out. (Failure code 910)	Chip light activation.	Loss of bevel gear preload causes slop and premature wear of bearings and gears. Secondary damage to other gear teeth and bearings due to metal contamination.	None.	II
First-Stage Servo Pump Spur Gear (65351-11176-101)	1	Transmit torque to first-stage hydraulic pump.	Spline fretting. (Failure code 406, 420)	None.	Progression of spline wear to failure by tooth shearing.	Elimination of drive for first-stage pump causes loss of first-stage hydraulic power.	II
			Web/shaft cracking. (Failure code 305)	None.	If crack propagates to fracture, first-stage hydraulic power is lost.	If crack propagates to fracture, first-stage hydraulic power is lost.	II
			Excessive wear of spur gear teeth. (Failure code 301)	Eventual chip light activation.	Secondary damage to other gear teeth and bearings due to metal contamination. Increase in operating vibration level due to deterioration of tooth profile.	Chip detectors prevent tooth profile disintegration (such a malfunction would cause loss of first-stage hydraulic).	II

Figure A-1. Typical FMEA.

component at a point in time. The relationships between h(t) and R(t) are as follows:

$$R(t) = e^{-\int_0^t h(\xi)d\xi} \qquad \text{(A-1)}$$

$$h(t) = -\frac{1}{R(t)} \cdot \left[\frac{\partial R(t)}{\partial t} \right] \qquad \text{(A-2)}$$

where e is the base of the natural logarithm
ξ is used as an integration variable to permit evaluation of the integral.

In the case of a single generic component failure mode, R(t) is defined as the Weibull reliability function as follows:

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}} \qquad \text{(A-3)}$$

where β is called the shape parameter
θ is called the size parameter

The corresponding hazard function, h(t), is given by

$$h(t) = \frac{\beta}{\theta} \left[\frac{t}{\theta} \right]^{\beta-1} \qquad \text{(A-4)}$$

If a particular failure mode is described by a combination of characteristics such as wearout or infant mortality, each must be described by a separate hazard function.

A.1.2.1 EXPERIENCE FAILURE MODE HAZARD FUNCTIONS

The technical approach given in the following section derives a method for computing the confidence interval of the hazard function from experience data when the reliability distribution is defined by the Weibull reliability function given in equation (A-3). The hazard function computed pertains to a single failure mode. The advantage of the method is that it allows the hazard functions to be approximately computed with any desired statistical confidence level and interval.

A.1.2.1.1 DISCUSSION

The data base used for this study contains instances of components that were removed from the aircraft that did not fail, such as no defect removals or high time removals. The data base also accounts for the operating time of components that were still in service when the data sample was terminated. Thus, there are data points that represent components that were not permitted to fail and which still had "good time" on them. Such data points are called censors. Since these components occur at different operating times, the data base is said to be multiply censored. The component operating times used for this study are the operating times since overhaul. This, rather than the time since new, is used because the gearbox after overhaul is presumed to have been restored to a new condition. This is equivalent to assuming that new gearboxes and overhauled gearboxes are from the same distribution.

A.1.2.1.2 ESTABLISHING CORRELATION

Before computing the hazard function parameters, a check is made to see if it is appropriate to associate a single size and shape parameter with a single failure mode. The check begins by plotting the data on Weibull graph paper, accounting for censored data that may occur between failures. The data points are then statistically tested for correlation. If the data are correlated, a visual check is made to see if a straight line can be passed through them.

Weibull graph paper plots the percentage of items failed under test versus the age of each item when it failed. The coordinates of the graph paper are

$$\left(\ln t_i,\ \ln\ln \frac{1}{1-F(t_i)} \right)$$

where t_i is the failure age of the i^{th} failure

$F(t_i)$ is the probability that any item under test will fail on or before time t_i

The correlation test tries to determine if a relationship exists between the percentage of items failed and the time of failure for data points of a particular failure mode. One difficulty in this process is that there is only one sample. If a large number of identical samples existed, the first failure of each would occur at different times, corresponding to different fractions of the total population. This produces a distribution of first failures approximated by the binomial probability distribution. It can be assumed that each successive failure represents the fraction of the population respresented by the median of all failures of the same order number; for example, all first failures have order number one, all second failures have order number two, etc. The "median rank" thus determined will be too high approximately 50 percent of the time, and too low 50% of the time. However, when a line is fitted to the data, the errors tend to cancel.

When censored data are contained in the sample, a method must be developed to determine the "median ranks". A good method is one described by Johnson.[14] In this method, the failures following a censored* item or items are assigned a mean order number by use of the following equation:

$$I_m = I_a + \frac{(N +)1 - I_a}{1 + N_s} \qquad \text{(A-5)}$$

where I_m is the mean order number
I_a is the previous order number
N is the number of units in the sample
N_s is the number of items at time of censor

The mean order numbers are used to determine interpolated median ranks, and a plot consisting only of failure points is used to determine correlation.

The procedure for plotting the data on Weibull paper depends on simply establishing the median ranks of failure data. All the data are first arranged with their operating times since overhaul put in ascending order. Failures are then ranked in ascending order. Each failure is assigned a median rank in accordance with its order. The median rank, $\bar{R}$, of the i^{th} order failure can be determined by expanding the binominal to i terms, equating it to 0.50, and solving for $\bar{R}$ as shown in equation (A-6).

$$0.5 = \sum_{j=0}^{i-1} \binom{N}{j} (1 - \bar{R})^{N-j} (\bar{R})^j \qquad \text{(A-6)}$$

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[14]Johnson, L. G., "The Statistical Treatment Of Fatigue Experiments", Elsevir, 1964, American Elsevir, N.Y.

*In Johnson's method censored items are called suspensions.

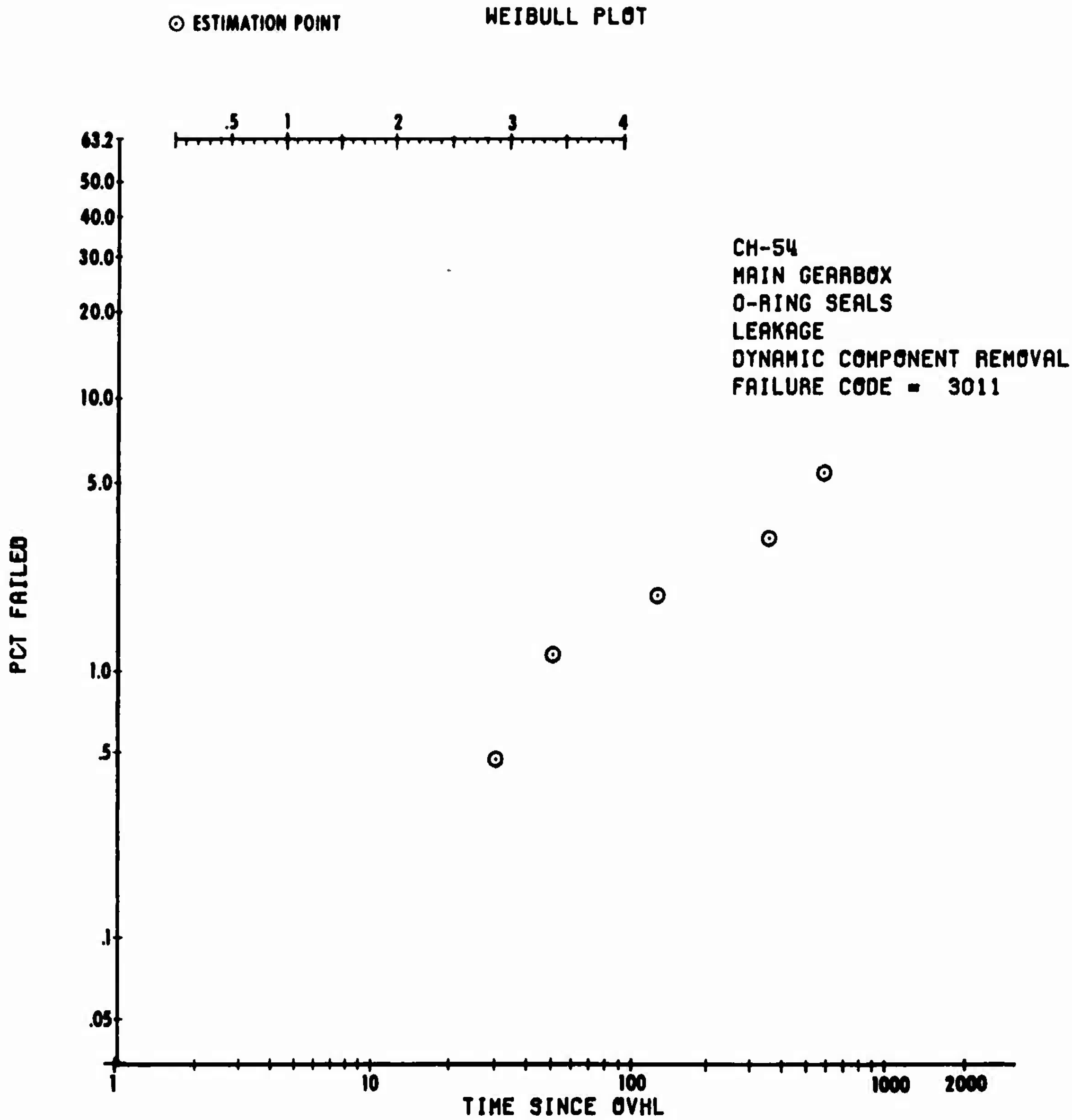

Figure A-2. Typical Weibull Plot

where N = the sample size

$$\binom{N}{j} = \frac{N!}{(n-j)\,!j!}$$

The solutions to equation (A-6) for sample sizes less than 50 can be found in Table A-1 of Reference 15. For sample sizes greater than 50, the median rank can be determined from equation (A-7).

$$\bar{R} = \frac{i - 0.3}{N + 0.4} \tag{A-7}$$

When censors are encountered, equation (A-5) is used to determine the mean order number. Median ranks are linearly interpolated from those of integral ordered failures. Figure A-2 shows the Weibull plot that results from this process.

If the unreliability, F(t), is of the form shown in equation (A-8), then it is easy to show that equation (A-9) follows.

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}} \tag{A-8}$$

$$\ln\ln\left[\frac{1}{1-F(t)}\right] = -\beta\ln\theta + \beta\ln t \tag{A-9}$$

The assumption that a particular mode's reliability is given by the Weibull distribution of the form $e^{-\left(\frac{t}{\theta}\right)^{\beta}}$ is verified by examining the data points. From equations (A-9) and (A-8) it follows that verification is achieved if a smooth straight line can be fitted through the data points. Determining if a correlation exists between $\ln\ln\left[\frac{1}{1-F(t)}\right]$ and $\ln t$ from the data points necessary in order to verify that a relationship exists between them. This is done by Fisher's correlation coefficient test. The method consists of postulating that no correlation exists and rejecting such a hypothesis. This is done by least-square fitting a line through data points calculating the correlation coefficient (see Reference 17 for the definition of a correlation coefficient) and comparing it with the maximum value

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[15] Mitchell, Robert A., "Introduction to Weibull Analysis," PWA 3001, January 6, 1967.

[16] Fisher, R. A., "Statistical Methods for Research Workers," Oliver & Boyd Ltd., Edinburgh and London, 1948.

[17] Thoman, Darrel R., Bain, Lee L., Antle, Charles, E., "Maximum Likelihood Estimation, Exact Confidence Intervals for Reliability, and Tolerance Limits in the Weibull Distribution," Technometrics, Vol. 12, No. 2, May 1970.

that can be expected by chance for the amount of data involved, if there was no correlation. The correlation coefficient is computed from the following equation:

$$r = \frac{\left[\left(\sum_{i=1}^{f} X_i Y_i \right) - \left(\sum_{i=1}^{f} X_i \cdot \sum_{i=1}^{f} Y_i \right) \right]}{\left[\left(\left(f \sum_{i=1}^{f} X_i^2 \right) - \left(\sum_{i=1}^{f} X_i \right)^2 \right) \left(\left(f \sum_{i=1}^{f} Y_i^2 \right) - \left(\sum_{i=1}^{n} Y_i \right)^2 \right) \right]^{1/2}}$$

where r = correlation coefficient

$X_i = \ln t_i$ where t_i is the age of the i^{th} item that failed

$Y_i = \ln\ln \left[\frac{1}{1-F\ (t_i)} \right]$ where $F(t_i)$ is the median rank of the i^{th} failure

f = the total number of failures

Fisher has shown that the statistic ρ is related to the "student t" statistic t as follows:

$$\rho^2 = \frac{t^2}{t^2 + f-2}$$

Once the data points are proved to have some correlation, a visual check is made to see if a straight line can be passed through them.

If the data proves to be uncorrelated or if it appears that a straight line cannot be fitted through the points, then the data must be partitioned, censored (see Reference 15), and replotted. Fisher's test is then repeated. Eventually, this process will yield a proper set of failure modes which have a single value of β and θ associated with them.

For the data plotted in Figure A-2, the computed correlation coefficient is .9747, and the statistic for the correlation to be valid within 90% is .8050. Hence, the data are correlated within 90% confidence.

A.1.2.1.3 HAZARD FUNCTION CONFIDENCE LIMITS

Once it has been verified that particular shape and size parameter can be associated with a single failure mode, experienced failure mode hazard function generation can commence. It has been seen by equations (A-1) and (A-2) that reliability and the hazard function are related. Having confidence in R(t) is equivalent to having the same confidence in h(t), even though the statistic used to test h(t) and R(t) may have different numerical values. This is easily seen if it is recognized that a hazard function is the instantaneous probability of failure, given that the component has survived to that point in time. Therefore, to have confidence in the cumulative process, one must have confidence in all the instantaneous processes which are a part of it. The relationship between the two statistics will be given later.

The confidence interval for h(t) is given by two statistics ϕ_L and ϕ_u, such that

$$\text{Probability } (\phi_L < h(t) < \phi_u) = 1 - \gamma \qquad \text{(A-10)}$$

where γ is the probability that the estimates of the hazard function are in error. The confidence interval for R(t) is given by two statistics Ψ_L and Ψ_u, such that

$$\text{Probability } (\Psi_L < R(t) < \Psi_u) = 1 - \gamma \qquad \text{(A-11)}$$

where γ is the probability that the estimates of reliability are in error. The relationship between ϕ and Ψ is then derived from equation (A-2) as follows:

$$\phi_L(t) = -\frac{1}{\Psi_u(t)} \left[\frac{\partial \Psi_u(t)}{\partial t}\right] \qquad \text{(A-12)}$$

$$\phi_u(t) = -\frac{1}{\Psi_L(t)} \left[\frac{\partial \Psi_L(t)}{\partial t}\right] \qquad \text{(A-13)}$$

The maximum likelihood estimator of reliability is the most probable value of reliability from the data that are available. This means that any other estimate of reliability will be less likely for any value time t. The values of β and θ, which describe the reliability when it is defined by the Weibull distribution, are computed to maximize the probability that events occur the way they did. This latter probability will hereafter be denoted as L.

Reference 17 shows that the distribution of the maximum likelihood estimator, $\hat{R}(t)$, of the reliability R(t) depends only on R(t) and N, where N is sample size involved. Reference 17 demonstrates this by showing that $\hat{R}(t)$ depends on β, θ, and t through R(t) and then studying the distribution of $\hat{R}(t)$ empirically. It should be noted that if reliability, γ_N, is defined as the number of components surviving a test compared to the total, N, at any time, t, then the variance of γ_N is always given by

$$\frac{R(t)\ (1 - R(t))}{N}$$

no matter how the probability distribution of γ_N is described.[18] This result follows from the properties of the binominal probability law, assuming that all N items are from the same statistical population. Thus it is expected that the variance of $\hat{R}(t)$ is a continually varying function of time.

It is important to note that the variance and the distribution of $\hat{R}(t)$ depend on the total sample size and not the number of failures. This will allow meaningful confidence intervals to be computed when they are only a few failures of a particular failure mode in a large sample.

The maximum likelihood estimates of reliability are directly computed from the maximum likelihood estimators of β and θ. This result follows from the fact that the maximum likelihood estimate of a function of several parameters is that function of the maximum likelihood estimate of these parameters.[19] A likelihood function L of n random variables x_1, x_2, ..., x_n expresses the relative likelihood that these variables assume a particular value, X_1, X_2, ..., X_n. In our study, X_i is the observed time of the i^{th} ordered failure ($X_i > X_{i-1}$). Reference 20, has shown that L for multiply censored data is given by

$$L = C \prod_{i=1}^{n} f(X_i;\ \theta,\ \beta) \prod_{i=1}^{k} (1-F(T_i))^{r_i} \qquad \text{(A-14)}$$

$$\text{when } N = n + \sum_{i=1}^{k} r_i$$

18. Parzen, E., "Modern Probability Theory and Its Application", John Wiley & Sons, Inc. Publishers, Sixth Printing, 1964, Page 229.

19. Mood, A.M., Graybill, F.A., "Introduction to the Theory of Statistics", McGraw-Hill Book Co., Inc. Second Edition, 1963.

20. Cohen A., Clifford, "Maximum Likelihood Estimation in the Weibull Distribution Based on Complete and on Censored Samples", Technometrics, Vol. 7, No. 4, Nov. 1965.

and where

$\prod_{i=1}^{n}$ is a product of functions 1 through n

C is a constant

$f(X_i;\theta,\beta)$ is the Weibull probability density function at time X_i and the size and shape parameters have the value θ and β

T_i is the ordered time ($T_i > T_{i-1}$) when the i^{th} censored item was removed from the aircraft.

$\sum_{i=1}^{k}$ is an algebraic sum of functions 1 through k.

r_i are the number of survivors that are removed at time T_i with the i^{th} censor.

$F(T_i)$ is cumulative unreliability, i.e., $1-R(T_i)$, which is a function of the same β and θ that $f(x_i;\theta,\beta)$ is given by.

n is the number of failures.

k is the number of censors.

N is the sample size.

The maximum likelihood estimates $\hat{\beta}$, $\hat{\theta}$ of β, θ are found by solving the following equations:

$$\frac{\partial L}{\partial \beta} = 0 \quad \frac{\partial L}{\beta \theta} = 0 \tag{A-15}$$

which results in $\hat{\beta}$ being found from the following equation:

$$0 = \frac{n}{\hat{\beta}} + \sum_{i=1}^{n} \ln X_i - \frac{n \sum_{i=1}^{n} X_i^{\hat{\beta}} \ln X_i + \sum_{i=1}^{k} r_i T_i^{\hat{\beta}} \ln T_i}{\sum_{i=1}^{n} X_i^{\hat{\beta}} + \sum_{i=1}^{k} r_i T_i^{\hat{\beta}}} \tag{A-16}$$

and then being substituted into the following equation:

$$\hat{\theta} = \left[\frac{1}{n}\left[\sum_{i=1}^{n} X_i^{\hat{\beta}} + \sum_{i=1}^{k} r_i T_i^{\hat{\beta}}\right]\right]^{1/\hat{\beta}} \tag{A-17}$$

Equation (A-14) may be solved using a commercially available program RTMIT ,which is part of the IBM System Scientific Subroutine Package.

To verify that the solutions obtained for $\hat{\beta}$, $\hat{\theta}$ maximize L of equation (A-14), the following theorem is used.[21]

"Let $z = f(x,y)$ be defined and have continuous first and second partial derivatives a domain D.
Let (x_o, y_o) be a point of D for which $\frac{\partial z}{\partial x}$ and $\frac{\partial z}{\partial y}$ are 0.
Let

$$A = \frac{\partial^2 z}{\partial x^2}(x_o, y_o), \quad B = \frac{\partial^2 z}{\partial x \partial y}(x_o, y_o), \quad C = \frac{\partial^2 z}{\partial y^2}(x_o, y_o)$$

Then a relative maximum at (x_o, y_o) exists if $B^2 - AC < 0$ and $A + C < 0$."

Letting $z = L$, $x_o = \hat{\beta}$, $y_o = \hat{\theta}$, $\hat{\theta}^* = \hat{\theta}^{\hat{\beta}}$ results in*

$$A = -\frac{n}{\hat{\beta}^2} - \frac{1}{\hat{\theta}^*}\left(\sum_{i=1}^{n} X_i^{\hat{\beta}} \ln^2 (X_i) + \sum_{i=1}^{k} r_i T_i^{\hat{\beta}} \ln^2 (T_i)\right) \tag{A-18}$$

$$B = \frac{1}{(\hat{\theta}^*)^2}\left(\sum_{i=1}^{n} X_i^{\hat{\beta}} \ln X_i + \sum_{i=1}^{k} r_i T_i^{\hat{\beta}} \ln T_i\right) \tag{A-19}$$

$$C = -\frac{n}{(\hat{\theta}^*)^2}\left(\sum_{i=1}^{n} X_i^{\hat{\beta}} + \sum_{i=1}^{k} r_i T_i^{\hat{\beta}}\right) \tag{A-20}$$

Hazard function confidence intervals are obtained by applying equations (A-12) and (A-13) to the reliability confidence limits. It is not generally possible to characterize the upper or lower confidence limit of the hazard function, $\phi_u(t)$ or $\phi_L(t)$, by a single β and θ when the hazard function is expressed by equation (A-4). This will lead to confidence limits crossing each other when the β describing the upper limit and the β

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21. Kaplan, Wilfred, "Advanced Calculus," Addison-Wesley Publishing Company, Inc., Fifth Printing, July 1959, Page 126.

* Equations (A-18) through (A-20) were derived from a Weibull reliability Distribution of the form $e^{-\frac{t^\beta}{\theta}}$ to simplify the algebra. Clearly, $\theta^* = \theta^\beta$. Since the maximum likelihood estimate of a function of several parameters is that function of the maximum likelihood estimate of these parameters, it follows that

$$\hat{\theta}^* = \hat{\theta}^{\hat{\beta}}$$

describing the lower limit are both greater than 2 !! Empirical distributions for the maximum likelihood estimate of reliability that were available were not complete enough to permit evaluation of equations (A-12) and (A-13). As a result, an asymptotic method was used. The method is accurate when sample sizes are greater than 100 provided that the lower reliability confidence limit exceeds .001. Accuracy is based on being able to evaluate the upper and lower confidence limits to within .001. When the sample size is less than 100, errors in the reliability assessment range from .002 to .007.

When the sample size is large, the confidence limits for reliability, R(t), can be obtained by assuming that the maximum likelihood estimate of reliability, R(t), is normally distributed with mean R and variance, V(R), equal to the Cramer-Rao Lower Bound. Hence, the lower confidence limit would be:

$$L_1 = R - u_\gamma \quad V(\hat{R})^{\frac{1}{2}} \tag{A-21}$$

where u_γ is the γ percentage point of the normal distribution (see Reference (A-d)). Similarly, the upper confidence limit would be

$$U_1 = \hat{R} + u_\gamma \quad V(\hat{R})^{\frac{1}{2}} \tag{A-22}$$

When the reliability distribution is defined by the Weibull distribution of the form $e^{-(\frac{t}{\theta})^\beta}$, equations (A-12) and (A-13) permit the upper and lower confidence limits for the hazard function to be evaluated as follows:

$$\phi_u = \frac{\hat{h}(t)\hat{R}(t) + \dfrac{u_\gamma}{2\left[V(\hat{R})\right]^{1/2}}\left[-2\hat{h}(t)V(\hat{R}) + \dfrac{2\hat{\beta}}{t}V(\hat{R})\right]}{\hat{R} - u_\gamma\left[V(\hat{R})\right]^{1/2}}$$

$$+ \frac{\dfrac{u_\gamma}{2\left[V(\hat{R})\right]^{1/2}}\left\{\dfrac{\left[\hat{R}\ln\hat{R}\right]^2}{N}\left\{-.514\dfrac{\hat{\beta}}{t} + 1.216\dfrac{\hat{\beta}}{t}\ln(-\ln\hat{R})\right\}\right\}}{\hat{R} - u_\gamma\left[V(\hat{R})\right]^{1/2}} \tag{A-23}$$

$$\phi_L = \frac{\hat{h}(t)\hat{R}(t) - \dfrac{u_\gamma}{2\,V(\hat{R})^{1/2}}\left\{-2\hat{h}(t)V(\hat{R}) + \dfrac{2\hat{\beta}}{t}V(\hat{R})\right\}}{\hat{R} + u_\gamma\left[V(\hat{R})\right]^{1/2}}$$

$$- \frac{\dfrac{u_\gamma}{2\left[V(\hat{R})\right]^{1/2}}\left\{\dfrac{\left[\hat{R}\ln\hat{R}\right]^2}{N}\left\{-.514\dfrac{\hat{\beta}}{t} + 1.216\dfrac{\hat{\beta}}{t}\ln(-\ln\hat{R})\right\}\right\}}{\hat{R} + u_\gamma\left[V(\hat{R})\right]^{1/2}} \tag{A-24}$$

where $\hat{h}(t)$ is the maximum likelihood estimate of the hazard function, N is the sample size, and $\hat{\beta}$ is the maximum likelihood estimate of the Weibull shape parameter.

A.1.2.2 POTENTIAL FAILURE MODE HAZARD FUNCTIONS

Potential failure mode hazard functions are computed from several analytical techniques that predict either the expected life or the probability of failure after a certain amount of operating time. These techniques generally provide a relative weighting of the failure modes to each other. To properly reflect the behavior of gearboxes where data were available, these techniques must predict a level of reliability that is compatible with no failures being experienced during that time. The techniques described below have been applied to the CH-53 nose gearbox.

A.1.2.2.1 INCIPIENT FAILURE MODES

There were a number of gearboxes that survived their overhaul period for which the condition of parts removed at overhaul indicated that failure was possible before the next overhaul period. Admittedly, engineering judgement must be used to distinguish between these parts and those for which failure is less likely. It is possible that all the parts could have continued in service and were merely replaced to maintain aircraft quality. Such potential failure modes are termed incipient. The discussion below assumes that the reliability distribution is defined by the Weibull reliability function of the form $e^{-(\frac{t}{\theta})^{\beta}}$. As in the previous section, the β's and θ's, which describe the hazard function as well as the reliability function, pertain to a single failure mode.

Incipient failure mode hazard function parameters, β and θ, are computed from gearboxes that had survived an entire overhaul period without removal but had parts replaced at overhaul whose condition indicated that failure was possible before the next overhaul. The expected number of failures from the historical data are equated to the number computed from probability theory. The equations are then solved to determine β and θ.

The number of failures expected (i.e.,the average number of failures) in the next overhaul period if overhaul were postponed for an additional TBO period is always given by

$$nQ \qquad \text{(A-25)}$$

where n is the number of gearboxes that survived the previous overhaul period, and Q is the probability of failure (i.e., the unreliability) in the next overhaul period given that a gearbox survived the previous overhaul period.

This result follows from the properties of the binomial probability law assuming that n items, new gearboxes and overhauled gearboxes, are from the same population no matter how the reliability distribution is defined (see Reference 18).

The conditional probability of failure in the interval $T_2 - T_1$ for any reliability distribution is $Q = \dfrac{Q(T_2) - Q(T_1)}{R(T_1)}$ (A-26)

where $Q(T_2)$, $Q(T_1)$ is the cumulative probability of failure from $T = 0$ to time $T = T_2$, T_1 (see Reference 22).

The field data indicated that many gearboxes were removed for their scheduled overhaul when their operating time since overhaul was less than the stated TBO. As a result, there was a distribution of times for T_1. To simplify the algebra and to get the largest population size in order that results not be overly conservative, the lowest operating time since overhaul was chosen. It will be seen shortly that the level of reliability which can be established with any degree of confidence is limited by the sample size. The time T_2 is operating time since overhaul if the gearbox had survived another full TBO, that is,

$$T_2 = T_1 + TBO$$

When the reliability distribution is defined by the Weibull reliability function, equation (A-26) becomes

$$Q = \frac{\left(1 - e^{-\left(\frac{T_2}{\theta}\right)^\beta}\right) - \left(1 - e^{-\left(\frac{T_1}{\theta}\right)^\beta}\right)}{e^{-\left(\frac{T_1}{\theta}\right)^\beta}}$$

$$q = 1 - e^{-\left(\left(\frac{T_2}{\theta}\right)^\beta - \left(\frac{T_1}{\theta}\right)^\beta\right)} \qquad \text{(A-27)}$$

If m is the number of expected incipient failures from the historical data, and equation (A-27) is substituted into equation (A-25), and the number of failures computed by (A-25) is equated to m, then

$$m = n\left(1 - e^{-\left(\left(\frac{T_2}{\theta}\right)^\beta - \left(\frac{T_1}{\theta}\right)^\beta\right)}\right) \qquad \text{(A-28)}$$

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22. Bazovsky, Igor, "Reliability Theory and Practices", Prentice-Hall, Inc., Publishers, Third Printing, 1963, Page 44.

B. Epstein[23] has shown that a lower limit estimate of reliability can be obtained if n items are placed on test for t_d hours and there are r failures as follows:

$$R(t_d) = \frac{1}{1 + \left[\frac{r+1}{n-r}\right] F_{\alpha;2r+2;\ 2n-r}} \tag{A-29}$$

where F is the upper α percentage point of the F distribution, with the corresponding degrees of freedom. The following statement can be made about this estimate of reliability. There is a probability of 1 - α that the true reliability for t_d hours is equal to or larger than R (t_d). This estimate is nonparametric and is valid for any reliability distribution.

If no failures occurred in time t_d, Equation (A-29) reduces to

$$r(t_d) = \frac{1}{1 + \left[\frac{1}{n}\right] F_{\alpha;\ 2r+2;\ 2n}} \tag{A-30}$$

Letting t_d = T, and the reliability distribution be defined the Weibull reliability function, Equation (A-30) becomes

$$e^{-\frac{T_1}{\theta}^{\beta}} = \frac{1}{1 + \left[\frac{1}{n}\right] F_{\alpha;\ 2;\ 2n}} \tag{A-31}$$

Equations (A-28) and (A-31) permit solution for β and θ to establish the hazard function of incipient failure modes. The results are

$$\beta = \frac{\ln \left\{ \frac{\ln\ (1 + (\frac{1}{n})\ F_{\alpha;\ 2;\ 2n}) - \ln(1 - \frac{m}{n})}{\ln\ (1 + (\frac{1}{n})\ F_{\alpha;\ 2;\ 2n})} \right\}}{\ln\ (\frac{T_2}{T_1})} \tag{A-32}$$

$$\theta = \frac{T_1}{\ln^{1/\beta}\ (1 + (\frac{1}{n})\ F_{\alpha;\ 2;\ 2n})} \tag{A-33}$$

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[23] Epstein, B., "Estimation From Life Test Data," IRB Transactions on Reliability and Quality Control, Vol. RQC-9 (April 1960).

An α = 50% was used for all incipient failure mode hazard function estimates (see Section A.1.2.4). As a result, $F_{\alpha;2;2n} \leq 1$. This means that the larger the value of n, the closer $R(t_d)$ of equation (A-30) approaches unity. It makes sense that fewer failures result in a higher percentage of survival. Conversely, the smaller the sample size, the lower is $R(t_d)$. Therefore, when there are no failures, small simple sizes, not time, limit the level of reliability that can be established.

A.1.2.2.2 INTERFERENCE THEORY

Interference theory is an analytical technique developed by the Rome Air Development Center (RADC). The method is documented in References 24 and 25. The basic idea behind interference theory is that a given part has certain physical properties which, if exceeded, will result in failure. The factor which may cause these properties to be exceeded is the stress imposed by the operating conditions. Thus, it is not the stress alone or the strength alone that is the determining factor, but the combined effect of the two. Within the limitations that the material be ferrous (carbon and alloy steels, stainless steels and other miscellaneous base material steels) or nonferrous (aluminum alloys, titanium alloys, magnesium alloys, cobalt alloys, copper alloys, nickel alloys and miscellaneous nonferrour alloys) and the failure mechanism be fatigue, the reliability of almost an unlimited number of parts can be predicted. While the method is based on considerable empirical data and has sound theoretical basis, RADC does not think the data sufficient to permit confidence intervals to be established for the probability of interference (failure).

Interference theory supposes that the strength of a manufactured item is not known with certainty prior to performing some test on it and that the stress induced by a load is not known with certainty prior to actually loading the part. For a multiplicity of reasons, strengths of seemingly identical parts are not exactly the same, and precisely what strength a part will have cannot be known until some type of strength test is performed. In the theory of probability, one says that the strength test of a part is a random variable. The same type of reasoning applies to the stress. Thus, for interference theory, one starts with the idea that strength is a random variable, say, X, and stress is a random variable, Y.

If X is any real number, then there is a probability that the random variable takes some value less than or equal to x. Symbolically, $Pr(X \leq x)$. One defines a probability distribution function, F(x), by the relation

$$F(x) = Pr(X \leq x) \qquad \text{(A-34)}$$

24. Lipson, C., et al, "Reliability Prediction - Mechanical Stress/ Strength Interference", RADC-TR-66-710, March 1967.

25. Lipson, C., et al, "Reliability Prediction - Mechanical Stress/ Strength Interference (nonferrous)", RADC-TR-68-403, February 1969.

In many applications F(x) has a derivative for every value of x, and one defines the probability density function, f(x), by

$$f(x) = \frac{dF(x)}{dx} \tag{A-35}$$

A property of f(x) is that

$$f(x)dx = Pr(x<X<x+dx) \tag{A-36}$$

(i.e., the probability density function multiplied by dx is the probability that X takes values in the neighborhood of x).

In the mathematical theory of interference, one assumes that the probability functions for the random variables X and Y are known. Failure is said to occur whenever the stress exceeds strength. From the known probabilities for the X and Y random variables, the probability of failure is given by the relationship

$$Pr\ (\text{failure}) = Pr(Y>X)$$

Reference (24) and (25) show this probability as given

$$Pr\ (\text{failure}) = \int_0^\infty \int_0^y f(x)g(y)dxdy \tag{A-37}$$

which can be reduced to one of two equivalent forms:

$$Pr\ (\text{failure}) = \int_0^\infty F(y)g(y)dy \tag{A-38}$$

or

$$Pr\ (\text{failure}) = 1 - \int_0^\infty f(x)G(x)dx \tag{A-39}$$

In general, these integrals cannot be expressed in terms of well-known functions and thus have to be integrated numerically. The numerical procedures and tabulated results are given in References 24 and 25.

The strength distribution used in the above expressions were derived from empirical data. For nonferrous materials, sets of strength data (S-N type) were studied. Each set was defined in terms of the type of material, type of loading, surface finish, stress concentration, heat treatment, temperature, and corrosive environment. Five distributions (Weibull, normal, log normal, largest extreme value, and smallest extreme

Value)* were least squares fitted to each set of the fatigue strength data, and the correlation was coefficient calculated to measure the goodness to fit. The distribution with the largest correlation coefficient was taken as the best-fitting distribution. For ferrous materials, the Weibull distribution was universally adopted, and the parameters associated with each set of strength data were determined by graphical methods.

The stress distribution used in the above equations is assumed to be normally distributed. The mean operating stress is calculated from the loads imposed on a given part. For the purpose of this study, these loads are conservatively assumed to be the maximum design operating loads. Furthermore, it is assumed that $\sigma = .1\mu$.

The difficulty in applying this method is that for complex structures, computing the operating stress becomes very difficult. It is also time-consuming when many simple structures are involved.

A.1.2.2.3 MISCELLANEOUS TECHNIQUES

While interference theory could be applied to gear pitting, tooth fracture, and bearing spalling, existing industrial standards were used since they are somewhat easier to apply. References 26 through 31 document the technique for gears. The technique is similar to the one above, in that an operating stress is compared with an allowable stress for a predetermined probability of failure. The advantage of this technique is that it permits easy computation of the stress distribution once the transmitted loads are known. The technique is intended specifically for gears in which the tooth contact has been developed to give a suitable pattern in the final mounting under normal operating loads.

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* The probability density functions for these distributions are defined in Appendix B.

26. "Design Procedures for Aircraft Engine and Power Take-Off Bevel Gears", AGMA Standard 431.01, March 1964.

27. "Design Procedures for Aircraft Engine and Power Take-Off Spur and Helical Gears", AGMA Standard 411.02, September 1966.

28. "Surface Durability (Pitting) of Spur Gear Teeth", AGMA Standard 210.02, January 1965.

29. "Surface Durability (Pitting) Formulas for Spiral Bevel Gear Teeth", AGMA Standard 216.01, Jan. 1964.

30. "Rating Strength of Spur Gear Teeth", AGMA Standard 220.02, August, 1966.

31. "Rating the Strength of Spiral Bevel Gear Teeth", AGMA Standard 223.01.

The first two are similar in the sense that they directly allow computation of the probability of failure as function of time (damage cycles). Once the probability of failure is known for two points the hazard function parameters β and θ can be calculated. For this study, one of the points chosen is the level of unreliability established by those gearboxes that survived the TBO period. The other level of unreliability at some future operating time is then computed by one of the above techniques.

Bearing Spalling - The technique for computing the hazard function parameters for bearing spalling is based upon SKF Industries Incorporated's method for calculating bearing lives, which is documented in Reference 32. The method allows the probability of failure to be calculated as a function of time. It accounts for bearing operating loads, materials, and processes, and lubrication. The value of   can be simply computed from the following expression:

$$\beta = \frac{\ln\left[\dfrac{\ln \dfrac{1}{1-\alpha}}{\ln (1.11)}\right]}{\ln \alpha_1}$$

where α is a level of unreliability less than 10% and α_1 is an adjustment factor corresponding to increased reliability that was developed from SKF fatigue test data on more than 2500 bearings. Substituting various sets of α and α_1 reveals that $\beta = 1.56 \pm .1$. The value of θ is computed with this value of β and the level of reliability $(1 - \alpha)$ at a given point in time computed from Reference 32. SKF's method assumes that proper consideration has been given to bearing size for the application. Undersizing of shaft and housing structures by using bearings which appear adequate from only a normal fatigue life viewpoint could lead to problems in fitting and misalignment which would tend to distort internal bearing loading and reduce the estimated fatigue life.

Gear Scoring - Gear scoring hazard function parameters are estimated much differently from those discussed above. Gear scoring is usually the result of the lubricant not being able to sustain a film of sufficient thickness to prevent metal-to-metal contact during gear meshing. Gear scoring, when present, usually results in very rapid gear wear. The criteria are characterized by the flash temperature index. The index can be thought of as a threshold, above which the Weibull distribution would have a slope (β) much greater than one and below which $\beta = 1$. The method for calculating the flash temperature index is documented in References 33 and

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32. "SKF Engineering Data", Copyright 1973, SKF Industries, Inc., Philadelphia, Pa.

34. The flash temperature index is based upon gears sliding relative to one another during meshing. It is computed from estimating the maximum temperature rise at the critical point of contact on the tooth surface and adding it to the oil inlet temperature. The index is compared with an allowable which represents a threshold value as mentioned above. The allowables are computed for a fixed* probability of scoring, for example, 5%.

In the current study β was assumed to be equal to one since there were no previous occurrences of failure. The value for θ, the size parameter of the Weibull distribution, is then calculated using the common chi-square statistic. If a new design were being evaluated, the flash temperature index would be computed to verify that it was below the allowable. The value for θ would then be estimated from previous generic data.

<u>Bearing Smearing</u> - Bearing smearing like gear scoring usually results from the lubricant not being able to sustain a film during operation. Bearings do not exhibit the same degree of sliding as gears. Generally, bearings mostly roll with only a small amount of intermittent skidding. While there are no standardized criteria, as for gears, most literature indicates that an elastohydrodynamic lubricant film parameter (Λ) of less than 1.5 usually results in excessive skidding (see References (32) and (35)). Λ is defined as the ratio of the lubricant film thickness to the composite surface finish. In the current study, there is no need to compute Λ since no failures were observed, so that β can be assumed to be equal to one by the reasoning used above for gears.

<u>Fretting Wear</u> - The hazard function parameters for generic devices exhibiting fretting wear are computed using the results of research documented in Reference 36 . The technique computes the average life based upon the number of cycles that it takes to remove a fixed amount of material from surfaces that are subject to fretting wear. The number of cycles are converted to a time and equated to the mean time to failure predicted for an item whose reliability is defined as a Weibull distribution, which is

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* Fixed means time invarient.

33. "Gear Scoring Design Guide For Aerospace Spur And Helical Power Gears", AGMA Standard 217.01, October 1965.

34. "Scoring Resistance Of Bevel Gear Teeth", Gear Engineering Standard, Gleason Works, March 1969.

35. Shurka, L.C., "Elastohydrodynamic Lubrication Of Roller Bearings", Journal of Lubrication Technology, April, 1970.

36. Stowers, L.F.; Rabinowicz, E.; "The Mechanism Of Fretting Wear", Journal Of Lubrication Technology 1973.

given by

$$\theta \cdot \Gamma\,(1 + 1/\beta)$$

where Γ is the gamma function

β, θ are the hazard function parameters

This along with the level of reliability established by gearboxes surviving to the TBO permit calculation of β and θ .

Exceptions - The proposed approach accounts for all potential failure mode hazard functions except cage fracture, nut loosening, bearing brinelling, excess wear of gear and bearing surfaces, and housing cracks. For these, analytical methods are not practical. It would be a difficult task to try to compute stresses that exist in a typical gearbox housing. In the case of cage fracture, the calculations would be meaningless. Most cages are overdesigned in terms of the stresses that are applied during normal operation. Cage fracture usually results from either lubrication failure or debris becoming lodged underneath the cage and exerting high local stresses. Stresses that cause locking devices on shafts to shear, which in turn allow nuts to back off, result from transient loadings that exist from time to time on a particular shaft. To predict these stresses would require a very complex dynamic analysis. Fortunately, there are generic data available to estimate the shape of the hazard function for gearbox housing cracks, but for the other modes this data is not generally available. As a result, engineering judgement must be used.

A.1.2.2.4 BOUNDARY CONDITIONS

The methods discussed in the previous paragraphs of Section A.1.2.2. provide a ranking of each failure mode's contribution to the total reliability established by all potential failure modes. The reliability predicted for all potential failure modes cannot be less than the level of reliability established by the lower confidence limit at each data point where there are no failures. This, in effect, constitutes a set of boundary conditions on the potential reliability predictions.

The level of reliability established by the lower confidence limit estimate is given by equation (A-30), that is,

$$R_L(t_p) = \frac{1}{1 + \frac{1}{p}\ F_{\alpha;2;2p}} \qquad \text{(A-40)}$$

where t_p is the operating time since overhaul of any data point in the samples of a particular gearbox

p is the number of gearboxes remaining in the sample at time t_p. p reflects the total sample size less any gearboxes that were previously removed as either failures or censors.

The level of reliability predicted for all potential failure modes is simply the product of the individual reliabilities associated with each mode. This assumes a series reliability model. As a result, the predicted reliability, $R_{pred}(t_p)$, at any time t_p is given by

$$R_{pred}(t_p) = \prod_{q=1}^{d} e^{-\left(\frac{t_p}{\theta_q}\right)^{\beta_q}}$$

$$= e^{-\left[\sum_{q=1}^{d} \left(\frac{t_p}{\theta_q}\right)^{\beta_q}\right]} \tag{A-41}$$

where d is the number of potential failure modes associated with a particular gearbox.

The boundary condition for predicted reliability is obtained by combining equations (A-40) and (A-41) as follows

$$e^{-\left[\sum_{q=1}^{d} \left(\frac{t_p}{\theta_q}\right)^{\beta_q}\right]} > \frac{1}{1 + \frac{1}{p} F_{\alpha;\ 2;\ 2p}} \tag{A-42}$$

Equation (A-42) must hold for all data points in the sample. Whenever it does not, each of the θ_q must be increased. The term inside the bracket of the exponent of equation (A-42) represents the expected number of failures in t_p hours. This is more easily understood if it is remembered that the exponent represents the area underneath the hazard function curve (see equation (A-1)). As a result, when equation (A-42) does not hold, it means that results are too conservative. To satisfy equation (A-42), the expected number of failures for each mode are proportionately decreased by the relative amount the mode contributes to the total. If the expected number of failures for each mode is $\left(\frac{t_p}{\theta_q}\right)^{\beta_q}$

and the amount for all modes is $\sum_{q=1}^{d} \left(\frac{t_p}{\theta_q}\right)^{\beta_q}$, then the number of expected failures that each mode must be decreased by, $ALLC_q$, because

$$ALLC_q = f^* \left\{ \frac{\left(\frac{t_p}{\theta_q}\right)^{\beta_q}}{\sum_{q=1}^{d} \left(\frac{t_p}{\theta_q}\right)^{\beta_q}} \right\} \tag{A-43}$$

where f is the excess number of failures predicted, which can be computed from the following equation

$$f = \ln\left\{\frac{1}{\left\{\frac{R_{pred}(t_p)}{R_L(t_p)}\right\}}\right\} \qquad \text{(A-44)}$$

The size parameter that permits the boundary conditions to be satisfied, θ_q, is computed from equation (A-45).

$$\theta_q^* = \frac{t_p}{\left\{\left(\frac{t_p}{\theta_q}\right)^{\beta_q} - ALLC_q\right\}^{1/\beta_q}} \qquad \text{(A-45)}$$

A.1.2.2.5 CATEGORY POTENTIALS

Many failures, as mentioned in Section A.1.1, could be placed in several categories, depending upon their severity. Frequently, failures were observed in one category but not in another; for example, failures were observed in the dynamic component removal failure category but not in the mission reliability category. The fact that there are fewer failures in the mission reliability category than in the dynamic component removal failure category is indicative of the amount of warning that inspections and fault warning systems provide for common failure modes. To apply the procedures of the previous section to mission reliability failures and safety-of-flight failures would result in an artificial reduction of potential failure mode hazard functions.

Potential failure mode hazard functions of mission reliability failures and safety-of-flight failures reflect experience data. When there were experience data for dynamic component removal failures but not any other category, the approach reflected it. If no experience data were available for dynamic component removal failures, hazard function parameters for mission reliability failures or safety-of-flight failures were assumed to be identical to the dynamic component removals. The only exception to this was when the number of failure modes in the mission reliability category or safety-of-flight category was less than the number in the dynamic component removal category.

When experience data existed only for dynamic component removal failures, hazard function parameters of other categories were computed from the reliability associated with these categories. The reliability for mission reliability failures must reflect either no dynamic component removal failures occurring or no mission aborts resulting from dynamic component removal failures. As a result, mission reliability is given by

P(no mission abort) = P(no dynamic component removal failure)

+ P(dynamic component removal failure) a P(no abort results from dynamic component removal failure) (A-46)

P(no abort results from dynamic component removal failure) is evaluated using equation (A-30) and the number of dynamic component removal failures, n. Equation (A-46) is applied to the last time that a dynamic component removal failure was observed, t, to evaluate P(no mission abort), assuming that the shape parameter is constant and that the size parameter increases from θ to θ_1. Thus, if the number of dynamic component removals were n,

equation (A-46) becomes:

$$e^{-\left(\frac{t}{\theta_1}\right)^{\beta}} = e^{-\left(\frac{t}{\theta}\right)^{\beta}} + \left(1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}}\right) \cdot \frac{1}{1 + \left(\frac{1}{n}\right) F_{\alpha;2;2n}} \quad \text{(A-47)}$$

This equation can then be used to solve for θ_1.

A.1.2.3 COMPONENT HAZARD FUNCTIONS

The component hazard function for any category of failure mode can be obtained by adding the contributions from generic component failure modes. Mathematical models for relating generic component failures to gearbox level failures were assumed to be serial for this study. This means that any single generic component failure can cause gearbox failure. To evaluate the gearbox level hazard function, equation (A-2) is used. For a serial model, the gearbox reliability, $R_g(t)$, is related to the generic component failure mode reliability, $R_i(t)$, as follows:

$$R_g(t) = \prod_{i=1}^{k} R_i(t) \quad \text{(A-48)}$$

where k is the number of generic component failure modes
$\prod_{i=1}^{k}$ is the product of functions 1 through k.

Substituting equation (A-48) into (A-2) results in

$$h_g(t) = \frac{1}{\prod_{i=1}^{k} R_i(t)} \cdot \frac{\partial}{\partial t}\left\{\prod_{i=1}^{k} R_i(t)\right\} \tag{A-49}$$

$$= \frac{-1}{\prod_{i=1}^{k} R_i(t)} \left\{\sum_{i-1}^{k} \frac{\partial R_i(t)}{\partial t}\right\} \prod_{\substack{i=1 \\ i\neq j}}^{k} R_i(t) \tag{A-50}$$

$$= - \sum_{j=1}^{k} \frac{1}{R_j(t)} \cdot \left\{\frac{\partial R_j(t)}{\partial t}\right\} \tag{A-51}$$

where $h_g(t)$ is the gearbox level hazard function. However, the individual terms of equation (A-51) are merely the generic failure mode hazard functions, $h_j(t)$. As a result, equation (A-51) becomes

$$h_g(t) = \sum_{j=1}^{k} h_j(t) \tag{A-52}$$

Generally, the significance of the combination of hazard functions is not equal to that level associated with each hazard function. However, the maximum likelihood estimate of the combination can be related to that associated with each individual failure mode. This result follows from the fact that the maximum likelihood estimate of a function of several parameters is that function of the maximum likelihood estimate of these parameters. Equations (A-21) and (A-22) show that for large sample sizes, the maximum likelihood estimate of reliability and the 50% confidence limit are synonoymous. As a result, if the 50% confidence level potential hazard functions and maximum likelihood estimates are combined, it is equivalent to specifying the gearbox level hazard function with 50% confidence. It is for this reason that the 50% confidence level estimate of potential failure mode hazard functions was used. It should be noted, however, that the level of confidence is valid only for those times included in the sample. For data points outside the sample, the hazard functions are only projections and not the actual 50% confidence level estimates.

APPENDIX B

PROBABILITY DENSITY FUNCTIONS USED BY INTERFERENCE THEORY

The probability density functions for the Weibull, the normal, the largest extreme value, the smallest extreme value, and logrithmic normal distributions are as follows:

(a) Weibull Distribution

$$\rho(x) = \frac{b}{\theta - x_o} \left[\frac{x - x_o}{\theta - x_o} \right] e^{-\left\{\frac{x - x_o}{\theta - x_o}\right\}^b}$$

$$x_o < x < \infty$$

where x = the independent variable (fatigue strength)
x_o = the lower bound of fatigue strength
θ = the characteristic fatigue strength
b = Weibull slope

(b) Normal Distribution

$$\rho(x) = \frac{1}{\sqrt{2\pi\sigma x}} e^{-\left.(x - \mu)^2 \right/ 2\sigma^2}$$

$$-\infty < x < \infty$$

where x = the independent variable (fatigue strength)
μ = population mean
σ = population standard deviation

(c) Largest Extreme Value

$$\rho(x) = \beta e^{-\beta(x-M)} e^{-e^{-\beta(x-M)}}$$

where $-\infty < x < +\infty$

x = the independent variable (fatigue strength)
β = intensity function (slope)
M = extreme value (mode)

(d) Smallest Extreme Value

$$\rho(x) = \beta e^{+\beta(x-M)} \; e^{-e^{+\beta(x-M)}}$$

$$-\infty < x < +\infty$$

where x = the independent variable (strength)
β = intensity function (slope)
M = extreme value

(e) Logarithmic Normal Distribution

$$\rho(x) = \frac{1}{\sqrt{2\pi}\,\sigma x} \; e^{-\frac{(\log x - \log\mu)^2}{2\sigma^2}}$$

x = the independent variable (fatigue strength)

population mean $= e^{(\log\mu + \frac{1}{2}\sigma^2)}$

Population variance $= e^{2\log\mu + \sigma^2} \cdot \left\{ e^{\sigma^2} - 1 \right\}$

log is natural logarithm.